THE EFFECTS OF NEW MATERIALS ON THE MIDSHIP SECTION DESIGN

by

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ABSTRACT

The trends toward ships of increasing size with increasing structural weights, progress in metallurgy and ever-better understanding of the loads on a ship and the interaction effects between its structural members point toward the use of new materials to effect savings in structural weight and displacement. The use of new materials means that new design criteria will have to be formulated to provide for their use.

This investigation first considers the relative advantages of steel, aluminum, beryllium and magnesium as structural materials and then proceeds to determine the savings to be expected and the need for a new σ_T criterion for the case of a high-yield steel construction. It indicates the nature of problems to be expected from dynamic loadings and the fact that ships of greater draft or greater depth with larger section modulus for a given draft could best benefit from the use of high-yield steel.

A method is advanced for determining whether design to meet a yield criterion or an instability criterion is indicated on the basis of the length, the maximum head of water above the keel expected and the type of material of construction for a ship. Proceeding further it outlines the advantages to be obtained from using aluminum for construction and of using a composite midship section of several materials.

The idea of a structural loading index as a measure of the loading intensity and a structural specific weight as a measure of hull weight are explained for use in comparing different designs.

The results of the investigation indicate that high yield steel can be of use in weight savings but that existing design criteria will have to be modified for its use. The length of an all-aluminum ship can be determined for which the maximum weight-savings benefit will accrue due to a design based on local (yield) requirements. Ships with composite midship sections of different materials may obtain benefits from lighter weight, an optimum location of the neutral axis at the mid-depth and an altered stress distribution pattern

which could change the expected instability requirements.

It is recommended that work be pursued further in this area to proceed further toward an optimization of the midship section design using new materials.

Thesis Supervisor: J. Harvey Evans
Title: Professor of Naval Architecture

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TABLE OF SYMBOLS

a $\equiv$ web frame spacing (in.)

$\equiv$ length over which load is applied on a vibrating free-free beam

b $\equiv$ longitudinal spacing (in.)

$\equiv$ buoyant force on ship (lb/ft)

c_1 $\equiv$ suitable coefficient for L in equation for σ_1

c_2 $\equiv$ assumed constant value for σ_2 in stress schedule (lb/in^2)

c_3 $\equiv$ constant in expression for plating sized on hydrostatic loading (lb/in^2-ft)

c_4 $\equiv$ $\sigma_1 + \sigma_2$ = constant for ship of given length and maximum head (lb/in^2)

c_5 $\equiv$ assumed constant relating longitudinal area to square of plating thickness

d_w $\equiv$ depth of web of longitudinal (in.)

g $\equiv$ acceleration of gravity (ft/sec^2)

k $\equiv$ critical stress coefficient for Bryan formula

k_1 $\equiv$ ratio of weight of stiffener to weight of plating

k_B $\equiv$ coefficient for stress at mid-length of side B in panel under uniform hydrostatic loading

n $\equiv$ shape parameter

p $\equiv$ load per unit length on vibrating free-free beam

r $\equiv$ radius of gyration for longitudinal and associated plating

t $\equiv$ shell plating thickness (in)

t_f $\equiv$ thickness of flange of longitudinal (in)

t_w $\equiv$ thickness of web of longitudinal (in)

w $\equiv$ weight of ship per foot (lb/ft)

x $\equiv$ distance fore and aft from $\boxtimes$ (ft)

A $\equiv$ area of longitudinal and effective plating (in^2)

A_f $\equiv$ area of flange of longitudinal (in^2)

A_s ≡ area of longitudinal (in^2)

A_w ≡ area of web of longitudinal (in^2)

B ≡ beam of ship (ft)

D ≡ depth of ship (ft)

E ≡ modulus of elasticity (lb/in^2)

E_t ≡ secant modulus of elasticity (lb/in^2)

E' ≡ 1.1E

GM_L ≡ longitudinal metacenter above center of gravity (ft)

H ≡ head of water above bottom shell plating (ft)

H_{max} ≡ maximum head of water above bottom shell plating (ft)

I ≡ moment of inertia of stiffener and effective plating (in^4)

$I_{⊗}$ ≡ moment of inertia of midship section (in^2-ft^2)

I_y ≡ mass moment of inertia of ship about transverse (y) axis

I_{yy} ≡ mass moment of inertia of virtual mass of water about transverse (y) axis

K ≡ coefficient of $(t/b)^2$ term in expression for critical stress (lb/in^2)

L ≡ ship length (ft)

≡ length of vibrating free-free beam

L' ≡ length of ship as determined by σ_{cr} and panel scantlings

M ≡ bending moment (ft-lb)

$M_{⊗}$ ≡ midship section bending moment (ft-lb)

T ≡ natural period of vibration of ship

T_1 ≡ natural period of wave encounter by ship

W_H ≡ weight of hull structure (tons)

W_m ≡ weight of machinery (tons)

W_p ≡ weight of payload (tons)

W_x ≡ weight of miscellaneous (tons)

δ_s $\equiv$ deflection of ship (ft)

Δ $\equiv$ displacement of ship (tons)

∇ $\equiv$ displacement volume of ship (ft^3)

γ $\equiv$ structural specific weight (lb/ft^2)

μ $\equiv$ Poisson's ratio

μ' $\equiv$ 1.1μ

ρ $\equiv$ material density (lb/in^3)

ρ_f $\equiv$ fluid density (lb/ft^3)

ρ' $\equiv$ 1.1ρ

σ_1 $\equiv$ hull girder bending (primary) stress (lb/in^2)

σ_2 $\equiv$ beam (secondary) stress (lb/in^2)

σ_3 $\equiv$ plate (tertiary) stress (lb/in^2)

σ_{cr} $\equiv$ critical or buckling stress (lb/in^2)

σ_y $\equiv$ yield stress (0.2% offset) (lb/in^2)

$\sigma_{0.7}$ $\equiv$ stress determined by intersection of line of slope 0.7 E through origin and σ/ϵ curve

$\sigma_{0.85}$ $\equiv$ stress determined by intersection of line of slope 0.85E through origin and σ/ϵ curve

τ $\equiv$ duration of loading of vibrating free-free beam

CHAPTER I

INTRODUCTION

The design of the midship section of a ship is one of the most interesting and, at the same time, one of the most challenging tasks that can be offered to the naval architect intent on optimization. When he tries to define the loads acting on his structure, he is faced with the problem of trying to constrain within certain well-defined limits one of the most unpredictable elements imaginable - the surface of the sea. Work by Lewis [17] and [18] and Korvin-Kroukovsky [14] among others indicate the magnitude of the problem of reducing the uncertainty of the sea state to a rational design criterion. While he can approximate the static loads to be expected with a reasonable degree of accuracy, he must at the same time be prepared to estimate dynamic loads from causes such as slamming and mooring which are functions of quite an independent variable - the ship's captain or master. Even if he could accurately define the static and dynamic loads to be expected, however, he is working with a complex grillage structure whose boundary conditions and interaction effects are not fully known and which is further complicated by having, at best, but a single axis of symmetry. In determining the worst possible condition for which to design, he is faced with three stresses, each determined in a manner different from the others, which may be additive or subtractive in different combinations dependent upon the state in which the ship may happen to find itself at any given time - hogging, sagging or still water. It may also be fully or only

partially loaded with an almost random weight distribution. The nice, neat optimum design for which the naval architect has been searching so long still remains partially hidden from him, its secrets guarded by the haze of uncertainty which still surrounds too many boundary conditions.

There exist at least three methods of attack in extending the optimization of the midship section design further along the path toward the least weight solution. One of these is to continue the investigation of the phenomena which affect the structural design - wave heights, dynamic loads, the interactions of structural members, boundary conditions and so forth. A second is to alter the properties of the materials themselves used in construction - such as yield strength, toughness, etc. - through alloying, heat treatment, irradiation or other methods. A third is to construct a composite midship section of several materials, making full use of the particular advantages of different types of materials wherever possible.

Work on the first of these attacks has been in progress from the time that the first primitive man with a stirring of thought got tired of hauling his tree trunk log in and out of the water and decided to hollow it out and save his back muscles a little effort. Work on the second method of attack is making great strides daily as the science of metallurgy is expanding at a rapid rate to meet the demands of industry, especially aircraft and missile industries. Work in the third category has been stimulated by the Navy's need to reduce topside weight on its warships to compensate for heavier electronics

equipment located ever higher which has provided incentive for the aluminum superstructure and mast concept.

Progress in metallurgy is continuously putting a variety of new materials in the hands of designers and improving "old" materials at the same time. Yield strengths on steel and aluminum have been increasing. Titanium and beryllium may be available for certain limited structural applications on a competitive basis with steel and aluminum in a matter of time if metallurgical progress continues at its present rate. While the problems of cost, corrosion, methods of fabrication and juncture (to mention a few) are still obstacles at this time, it is not unreasonable to assume that at some future date the prospects will be so bright as to bring them into greater use. The transition from wooden to steel ships and from riveted to welded construction did not occur overnight.

When one considers a material for use in construction, he must be familiar with many of its properties in order to utilize it effectively. In most cases one must weigh the merit of one property against the liabilities of another in reaching a decision as to what material to use (although cost, availability, ease of fabrication and experience arguing in favor of steel tend to drown out arguments from other metals). What, then, are the properties which effect the use of a material?

Perhaps the two most important properties of a material are its modulus of elasticity and yield strength. One customarily designs a structure to carry a given load without exceeding certain permissible deflections and without exceeding

a stress level equal to the yield stress divided by an appropriate factor of safety. For slender structural members one faces the problem of premature failure, however, and here the modulus of elasticity enters the problem since it is a measure of the inherent stability of the material as evidenced by the resistance to deformation under load.

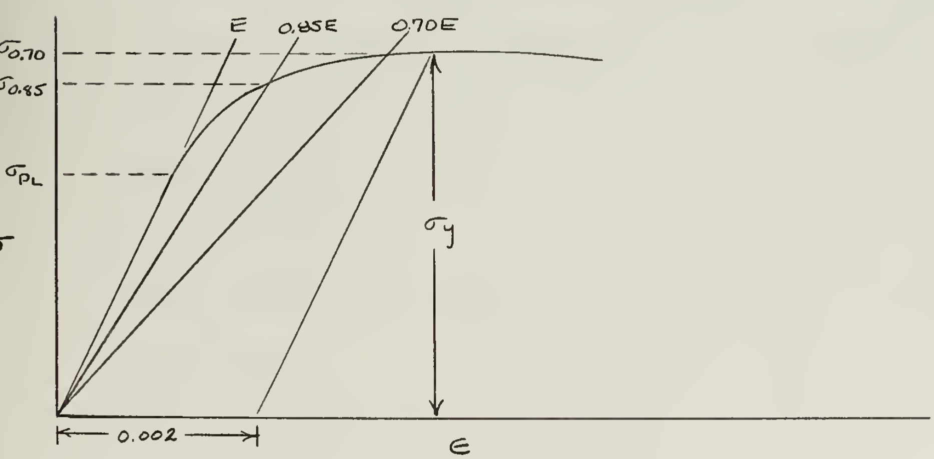
In considering the effect of the modulus of elasticity, however, one must also consider the effect of the proportional limits of the material on the design, being careful to use the tangent modulus (or the modulus at the particular design stress considered). The proportional limit is quite important for a material with a large modulus of elasticity value but with a low proportional limit would realize the full effect of the large modulus value only below the proportional limit which might be at a stress level which is too low to be feasible from the economic aspect. One can visualize the proportional limit as being the point at which the internal distortions between lattices on slip planes take on a permanent nature and provide internal eccentricities which hasten premature failure. The incorporation of the effect of the change in the modulus of elasticity value beyond the proportional limit in buckling considerations to supplant the early Euler, Bryan, etc. formulations has been made in works by Bleich [3] and [4], Gerard and Becker [11] and others for the buckling problem. Gerard and Becker have formulated a relationship for values of the modulus of elasticity in the region beyond the elastic limit which is as follows:

$$\frac{E}{E_t} = \frac{E}{d\sigma/d\epsilon} = 1 + \frac{3n}{7}\left(\frac{\sigma}{\sigma_{0.7}}\right)^{n-1} \qquad (1)$$

where $\sigma_{0.7}$ = stress at secant modulus 0.7E

n = shape parameter as below:

n	Material
3	1/4 hard to full hard 18-8 stainless steel, with grain 1/4 hard 18-8 stainless steel cross grain
5	1/2 hard and 3/4 hard 18-8 stainless steel cross grain
10	Full hard 18-8 stainless steel, cross grain 2024-T and 7075-T aluminum-alloy sheet and extrusion 2024R-T aluminum-alloy sheet
20-25	2024-T80, 2024-T81 and 2024-T86 aluminum-alloy sheet 2024-T aluminum-alloy extrusion SAE 4130 steel heat-treated up to 100,000 psi ultimate stress
35-50	2014-T aluminum-alloy extrusion SAE 4130 steel heat-treated above 125,000 psi ultimate stress
∞	SAE 1025 (mild) steel



$$n = \frac{1 + \ln(17/7)}{\ln(\sigma_{0.70}/\sigma_{0.85})}$$

Still another parameter which affects the building or critical stress of a member is Poisson's ratio for the material in question. At this point, however, the effect is quite small because Poisson's ratio for most metals in use runs about 0.3. Even though the variation in μ is small, when its effect is combined with that of the modulus of elasticity there can be a notable, even if small, variation in the critical stress for a structure of a given geometry.

Consider, for example, the standard formula for critical stress for a homogeneous plate below the proportional limit. Then

$$\sigma_{cr} = \frac{k\pi^2 E}{12(1-\mu^2)} \left(\frac{t}{b}\right)^2 \tag{2}$$

Looking at the material effects on the buckling stress (the other terms being functions of boundary conditions and geometry) we find that the modulus of elasticity and Poisson's ratio both affect the results as shown by the term

$$\frac{E}{1-\mu^2}$$

This is not a constant except for a homogeneous batch of a certain type of material. For example, consider the variation among three types of steel whose properties can be found in [16]:

Material	E	μ	$E/1-\mu^2$
18.8 stainless steel	27.6×10^6	0.305	30.45
Cast steel	28.5×10^6	0.265	30.75
Cold rolled steel	29.5×10^6	0.287	32.15

Thus within steel alone there can be at least a 5.75% variation in critical stress depending upon the type of steel used. Since plate thickness is proportional to the square root of the critical stress and weight is proportional to thickness, the weight variation for the three types of material would vary only on the order of 2.4% which, although small, is noticeable. The transition to different types of materials brings other values of the factor $E/1-\mu^2$. A comparison of several types of materials on a yield and on an instability basis is shown below for material mechanical property values obtained from [15], [16], [20] and [33].

Material	σ_y (lb/in²)	E (lb/in²)	μ	ρ (lb/in³)	$E/1-\mu^2$ $\times 10^{-6}$	$E/\rho(1-\mu^2)$ $\times 10^{-6}$	σ_y/ρ $\times 10^{-3}$
Pure Aluminum	21,000	10×10^6	0.33	0.098	11.25	11.5	214.5
2017 Aluminum	40,000	10.4×10^6	0.33	0.101	11.69	11.55	396
2024 Aluminum	57,000	10.6×10^6	0.33	0.100	11.90	11.90	570
7075 Aluminum	72,000	10.4×10^6	0.33	0.101	11.69	11.55	713
Pure Magnesium	27,000	6.5×10^6	0.35	0.0628	7.4	11.79	430
18-8 Stainless Steel	35,000	27.6×10^6	0.305	0.287	30.45	10.6	122
Cold-Rolled Steel	—	29.5×10^6	0.287	0.287	32.15	11.2	—
Beryllium vacuum hot-pressed from QMV powder	32,100	44.4×10^6	0.024	0.0658	44.4	67.5	488
Beryllium hot extruded from pressed QMV powder	39,500	41.4×10^6	0.032	0.0658	41.4	62.9	600
Be-Ni Alloy cast, solution-annealed & aged	150,000	27×10^6	0.05	0.293	27.1	9.25	511
Be-Cu casting alloy	85,000	18.5×10^6	0.05	0.292	18.56	6.35	291
Titanium	70,000	16×10^6	0.34	0.163	18.1	11.1	430

The values $\frac{E}{\rho(1-\mu^2)}$ and $\frac{\sigma_y}{\rho}$ act as indices of the strength/weight ratios of the various metals and alloys for instability and yield design criteria respectively. For a design which is faced with an instability problem one would want a large value of $\frac{E}{\rho(1-\mu^2)}$, and beryllium and its alloys show the most striking advantage here due to the fact that beryllium combines the advantage of light weight with a very high modulus of elasticity. On the other hand, for a design subject only to the yield criterion, the value of $\frac{\sigma_y}{\rho}$ is the dominant strength/weight index and aluminum clearly shows its merit for this case.

Another interesting result is the closeness of aluminum, steel and titanium when judged on the $\frac{E}{\rho(1-\mu^2)}$ basis, titanium weighing only about half as much as steel but having a modulus of elasticity which is also only half that of steel. The same relationship also holds true for aluminum with the exception that the factor here is one-third vice one-half.

On a yield design basis 7075 aluminum holds a decided advantage over the other metals considered, with steel finishing a poor last. Magnesium and titanium are comparable on this basis but are less advantageous than beryllium.

If one considers the possibilities of advances in metallurgical technology which will bring changes in the mechanical properties of existing metals - such properties as E, μ and σ_y - it is interesting to consider the effect of each on the weight of the structure and to determine which offer the greatest reward.

Considering a ship's bottom structure which is the heaviest area of the midship section (as evidenced by the fact that the neutral axis of the midship section nearly always lies below the mid-depth of the section) we can set up an expression for the weight of a unit area of the bottom structure and then proceed to analyze this for the effects which variations in material characteristics would play.

As a representative unit area of the bottom structure let us take the plating between two web frames and two longitudinals along with one of the longitudinals. To be rigorously correct we should also add the weight of one web frame between the adjacent longitudinals so as to insure the inclusion of all the longitudinal and transverse weight effects but, since the normal midship section design problem addresses itself to the problem of insuring adequate longitudinal strength and leaves the solution of the transverse strength problem to a separate, independent calculation and since the weight of plating and longitudinals constitute the major proportion of the weight to be minimized, we shall not include the web frame effects for purposes of simplifying what would otherwise be an expression whose complexity overshadowed its usefulness.

$$\text{weight/unit area} = \gamma = \frac{\text{weight of plating} + \text{weight of longitudinal}}{\text{web frame spacing x longitudinal spacing}}$$

Weight of plate = ρtab

Weight of longitudinal = $\rho a A_s$

Consider first the case of yield design, i.e., one in which instability is no problem.

Then the thickness of the bottom plating will be a function of the aspect ratio of the panel and the head of water acting on it. The common expression for a panel design for this case is given by

$$\sigma = \frac{1}{2} k \rho H \left(\frac{b}{t}\right)^2 \frac{1}{144} \tag{3}$$

as shown in figure 1. For our purposes let us assume

$$\rho = 64 \text{ lb/ft}^3 \qquad a \geqq 1.6b$$

For the case of the longitudinally framed ship the assumption that $a \geqq 1.6b$ generally holds and furthermore the stress value of concern is that orthogonal to the short side of the plate.

Using the definitions of stresses given by Professor Evans in his paper on the structural analysis and design integration of the midship section [8] we can say that $\sigma_y \geqq \sigma_1 + \sigma_2 + \sigma_3$ for a rational design.

Since the σ value in the expression for the bottom plating thickness is the σ_3 value, the σ_y value is fixed by the material being used, the σ_1 value is a function of bending moment and section modulus (which is generally approximated initially by an expression which is a function of ship length) and since σ_2 stresses are generally small and essentially constant, let us say

$$\sigma_1 = c_1 f(L)$$
$$\sigma_2 = c_2$$

whence, rearranging:

$$\sigma_3 \leq \sigma_y - \sigma_1 - \sigma_2 \quad \text{or} \quad \sigma_3 \leq \sigma_y - c_1 f(L) - c_2$$

Then, rearranging the expression for σ_3, combining all the known constants and recognizing that $K_B = 0.685$ for $a/b \geqslant 1.6$ we have, from (3):

$$\left(\frac{t}{b}\right)^2 \leq 6.57\,\frac{\sigma_3}{H} \leq \frac{c_3\left[\sigma_y - c_1 f(L) - c_2\right]}{H} \tag{4}$$

whence

$$\left(\frac{t}{b}\right)^2 \leq \frac{H}{c_3\left[\sigma_y - c_1 f(L) - c_2\right]} \tag{5}$$

and

$$\frac{t}{b} = \left\{\frac{H}{c_3\left[\sigma_y - c_1 f(L) - c_2\right]}\right\}^{1/2} \tag{6}$$

Now

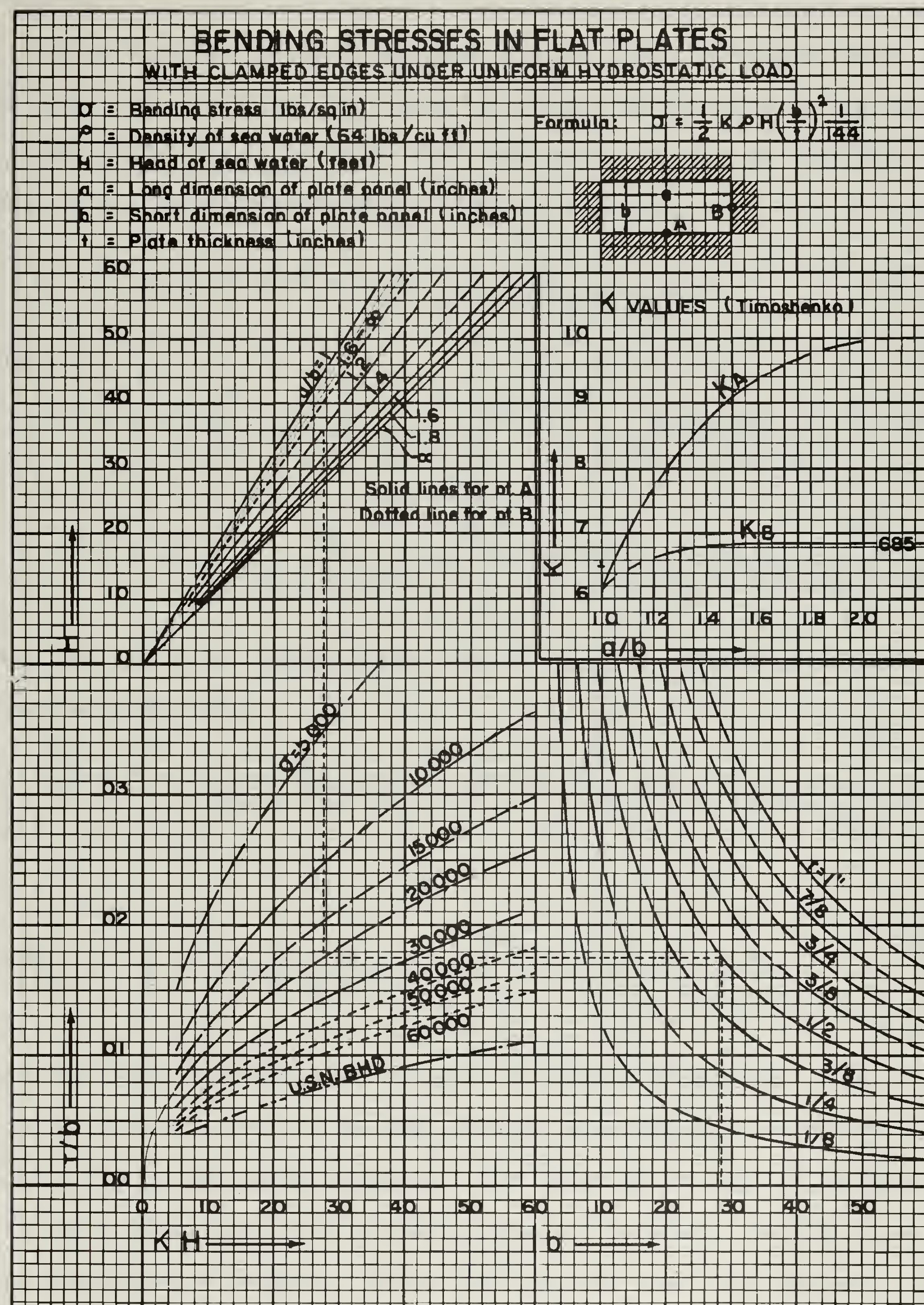
$$\gamma = \frac{\rho tab + \rho a A_s}{ab} = \frac{\rho tb + \rho A_s}{b} = \rho\left[b\left(\frac{t}{b}\right) + \frac{A_s}{b}\right] \tag{7}$$

Substituting the value for (t/b) from (6) into (7):

$$\gamma = \rho\left[b\left\{\frac{H}{c_3\left[\sigma_y - c_1 f(L) - c_2\right]}\right\}^{1/2} + \frac{A_s}{b}\right] \tag{8}$$

The value of A_s for the yield case is not rigorously defined except for the fact that the longitudinals must be heavy enough to provide a clamped boundary condition to the long edge of the plate. Gerard and Becker in [11] mention that for $b/t > 200$ most stiffeners will effectively clamp the plate edge, but since values of b/t for ship bottom structures generally run considerably less than this (see appendix A for t/b values corresponding to a variety of conditions and yield stresses) the selection of an optimum stiffener size for the yield case is somewhat poorly defined. Since the plating is continuous across the stiffener and hydrostatic pressure acts on both sides, it would seem that the symmetric hydrostatic

FIGURE 1



BENDING STRESSES IN FLAT PLATES
WITH CLAMPED EDGES UNDER UNIFORM HYDROSTATIC LOAD
σ = Bending stress (lbs/sq in)
ρ = Density of sea water (64 lbs/cu ft)
H = Head of sea water (feet)
a = Long dimension of plate panel (inches)
b = Short dimension of plate panel (inches)
t = Plate thickness (inches)
Formula: σ = 1/2 K ρ H (b/t)² 1/144
K VALUES (Timoshenko)
KA
KB
.685
a/b
Solid lines for pt A
Dotted line for pt B
σ = 5,000
10,000
15,000
20,000
30,000
40,000
50,000
60,000
U.S.N. BHD
t = 1"
7/8
3/4
5/8
1/2
3/8
1/4
1/8
KH
b
t/b

loading would tend to provide some support against rotation of the stiffener and plating, thus contributing to the edge support.

From BuShips section modulus graphs [34], assuming that the smallest stiffener for each thickness of plating is adequate for the yield case, we find that the relationship of minimum A_s to t can be approximated as (see figure 2):

$$A_s \approx 5.39t^2 = 5.39 \frac{Hb}{c_3\left[\sigma_y - c_1 f(L) - c_2\right]} \tag{9}$$

Thus

$$\gamma = \rho\left\{ b\left[\frac{H}{c_3\left[\sigma_y - c_1 f(L) - c_2\right]}\right]^{1/2} + \frac{1}{b}\,\frac{5.39\ Hb^2}{c_3\left[\sigma_y - c_1 f(L) - c_2\right]}\right\} \tag{10}$$

$$\gamma = \rho b\left\{\frac{H}{c_3\left[\sigma_y - c_1 f(L) - c_2\right]}\right\}^{1/2}\left\{1 + 5.39\left[\frac{H}{c_3\left[\sigma_y - c_1 f(L) - \sigma_2\right]}\right]^{1/2}\right\} \tag{11}$$

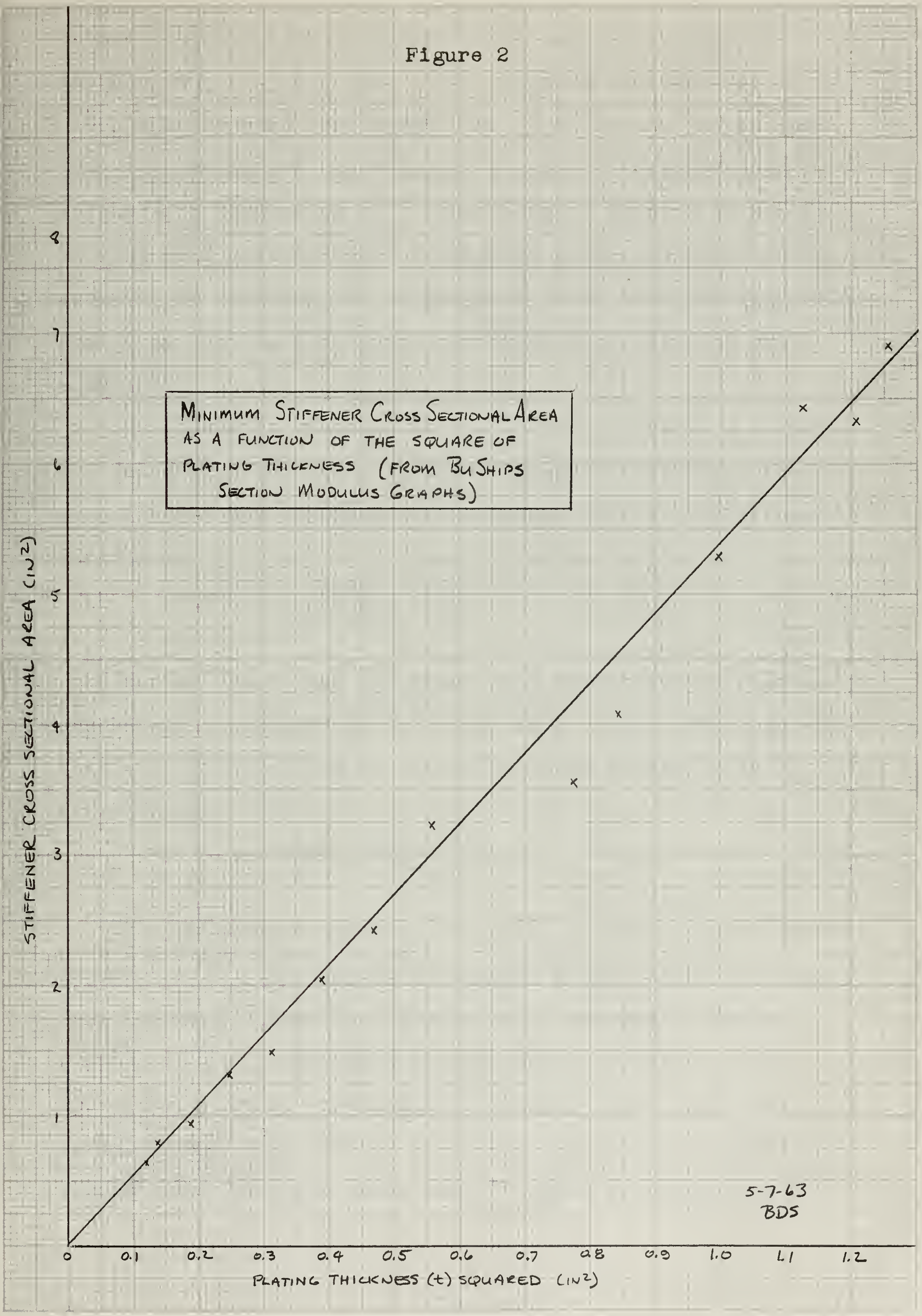
Thus the rates of change with respect to the various material parameters become:

$$\frac{\partial T}{\partial \rho} = b\left\{\frac{H}{c_3\left[\sigma_y - c_1 f(L) - c_2\right]}\right\}^{1/2}\left\{1 + 5.39\left[\frac{H}{c_3\left[\sigma_y - c_1 f(L) - c_2\right]}\right]^{1/2}\right\} \tag{12}$$

$$\frac{\partial \gamma}{\partial \sigma_y} = -\frac{1}{2}\,\rho b\left\{\frac{H}{c_3\left[\sigma_y - c_1 f(L) - c_2\right]^3}\right\}^{1/2}\left\{1 + 10.78\left[\frac{H}{c_3\left[\sigma_y - c_1 f(L) - c_2\right]}\right]^{1/2}\right\} \tag{13}$$

Thus the rate of change of weight of bottom structure with density varies directly as the design geometry and boundary conditions as we would suspect. The rate of change of weight of bottom structure with yield strength, however, varies in a more complicated manner. From [13] we see that the latter

Figure 2


MINIMUM STIFFENER CROSS SECTIONAL AREA AS A FUNCTION OF THE SQUARE OF PLATING THICKNESS (FROM BUSHIPS SECTION MODULUS GRAPHS)
STIFFENER CROSS SECTIONAL AREA (IN²)
PLATING THICKNESS (t) SQUARED (IN²)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1.1
1.2
1
2
3
4
5
6
7
8
5-7-63
BDS

varies roughly as the inverse of the expression $(\sigma_y - c_4)^{3/2}$ where $c_4 \equiv \sigma_1 + \sigma_2 \equiv c_1 f(L) + c_2$ = assumed constant for a given ship length. The larger the σ_y value the larger the $(\sigma_y - c_4)$ value and hence the more rapid the decrease in weight with increasing σ_y. Since changes in density would be most difficult to achieve (density reduction), the major advances in reducing the weight of a yield-based design would come from further increases in the yield strength of the material.

Now consider the case of instability. Assuming that we are faced with premature failure through instability, the expression for the critical (or buckling) stress as mentioned earlier is

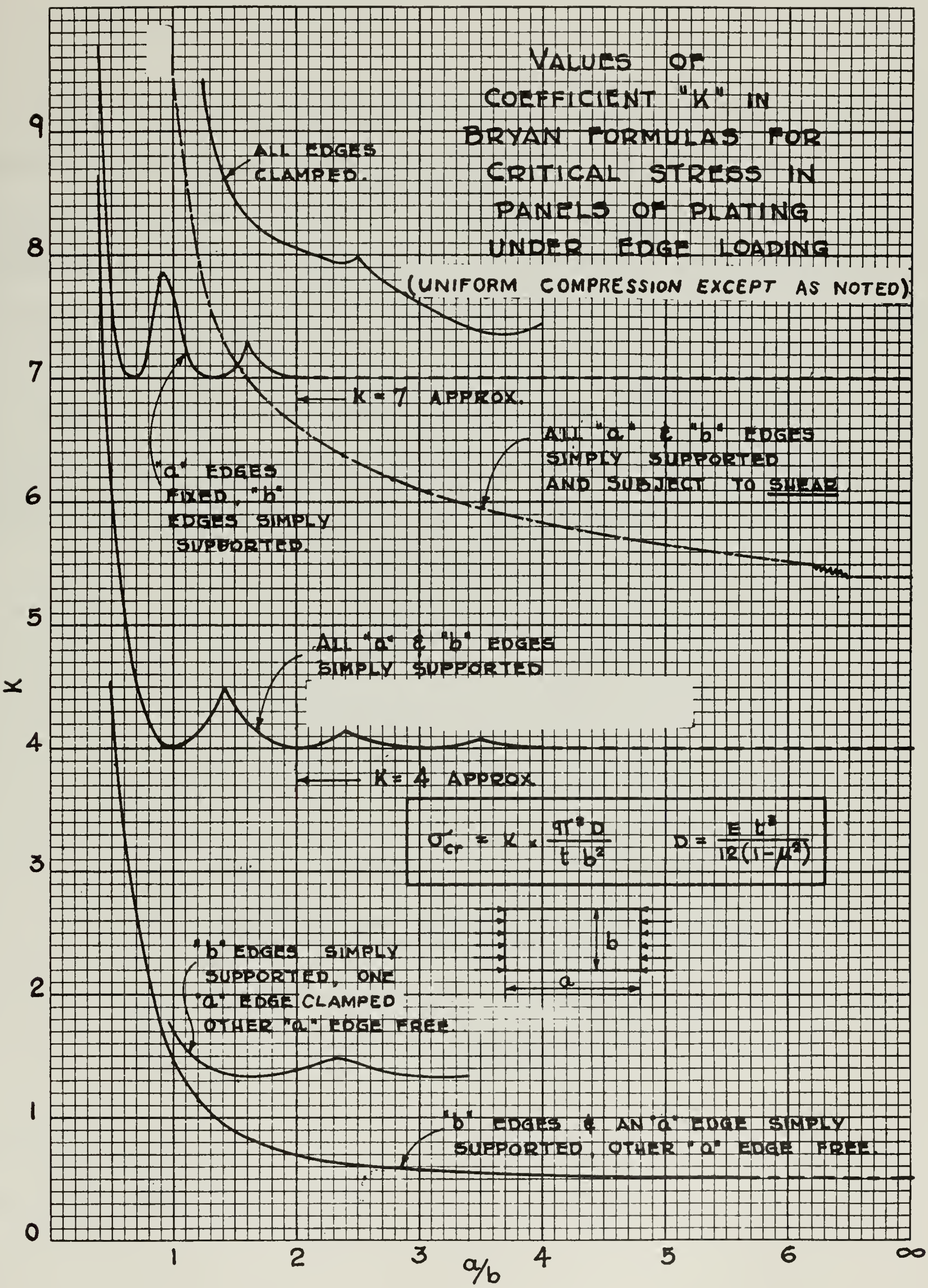
$$\sigma_{cr} = \frac{k\pi^2 E}{12(1-\mu^2)} \left(\frac{t}{b}\right)^2 \tag{2}$$

Now we would like to insure that the structure remains stable when subjected to the expected σ_1 value occasioned by the design bending moment amidships which implies that $\sigma_{cr} \geqslant \sigma_1$ for stability. Then

$$\left(\frac{t}{b}\right)^2 = \frac{12(1-\mu^2)\sigma_1}{k\pi^2 E} \tag{14}$$

The boundary conditions for this case are subject to some argument as to the degree of clamping which exists but surely some degree of rotational restraint is imposed by the web frames and the longitudinals to raise the critical stress above the critical stress for the simply supported plate. Assuming that this support is on the order of that given in figure 3 for the case where the "a" edges are fixed and "b"

FIGURE 3



VALUES OF COEFFICIENT "K" IN BRYAN FORMULAS FOR CRITICAL STRESS IN PANELS OF PLATING UNDER EDGE LOADING
(UNIFORM COMPRESSION EXCEPT AS NOTED)
ALL EDGES CLAMPED.
K = 7 APPROX.
ALL "a" & "b" EDGES SIMPLY SUPPORTED AND SUBJECT TO SHEAR.
"a" EDGES FIXED, "b" EDGES SIMPLY SUPPORTED.
ALL "a" & "b" EDGES SIMPLY SUPPORTED
K = 4 APPROX.
$\sigma_{cr} = K \times \frac{\pi^2 D}{t\, b^2}$ $D = \frac{E\, t^3}{12(1-\mu^2)}$
b
a
"b" EDGES SIMPLY SUPPORTED, ONE "a" EDGE CLAMPED OTHER "a" EDGE FREE.
"b" EDGES & AN "a" EDGE SIMPLY SUPPORTED, OTHER "a" EDGE FREE.
K
0
1
2
3
4
5
6
7
8
9
a/b
∞

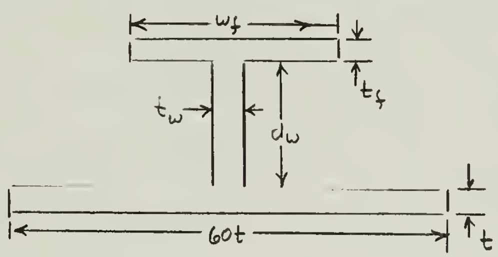
edges simply supported, the coefficient k will be $\geqslant 7$ for a/b ratios $\geqslant 1.6$. Thus

$$\left(\frac{t}{b}\right)^2 = \frac{c_1 f(L)(1-\mu^2)}{5.75E} \tag{15}$$

Also the stiffener-plating combination must meet a certain minimum slenderness ratio for stability, this value usually being on the order of 30 for the bottom sections. This slenderness ratio is by no means a definitive limiting value as is shown by figures 4 and 5, however.

Assume $L/r \leqq 30$. Then $r \geqslant a/30$

But $r = \sqrt{I/A}$ and for the section of combined plating (using an effective width of 60t as per the BuShips Section Modulus Graphs) and stiffener as shown below:



A = area of longitudinal and effective plating

I = moment of inertia of longitudinal and effective area of plating

A_f - area of flange of longitudinal

A_w - area of web of longitudinal

$$A = A_s + 60t^2 \tag{16}$$

$$A_s = A_f + A_w = w_f t_f + d_w t_w \tag{17}$$

Figure 4

L/R RATIOS AND ULTIMATE STRENGTH IN COMPRESSION OF MAIN DECKS OF VARIOUS CLASSES OF SHIPS

SHIP	MAIN DECK PLATING	MAIN DECK LONGITUDINALS	LONG'L. SPACING	WEB FR. SPACING	l/r	ULTIMATE COMPRESSIVE STRENGTH OF PLATING FROM TMB #469	ULTIMATE COMPRESSIVE STRENGTH OF PLATING & LONG'L. COMBINED FROM BU. COL. TABLES
DD 364	19# MS	10x5¾x21# I MS	30"	7'	25	26000	34600
DD 445	20# STS	6x4x12# I-T MS	30"	7'	48	34000	31200
DD 692	20# STS	6x4x8.25#T HTS	30"	7'	48	34000	39300
DE(Tev)	20.4#MS	4x3x8.5# L MS	24"	7'	68	30600	26500
CL 55	36.5 STS	8x6½x24#I-T MS	43"	16'	88	41000	21400
CL 144	40# STS	8x5¼x17#I-T MS	43"	16'	105	43000	17500
CA 68	45# STS	8x6½x24#I-T MS	43"	16'	95	46000	19700
CA 139	40# STS	8x6½x24#I-T MS	43"	16'	105	43000	17500
CV 9	100# STS	10x8x33#I-I MS	90"	16'	119	46000	15000
CLC 1	40# STS	8x5¼x17#I-T HTS	43"	16'	106	43000	19000
CLK 1	35# STS	8x4x15# I-T HTS	42½"	14'	94	40000	22400
DD 927	30# STS	8x5¼x17#I-T HTS	33"	8'	42	42500	41100

Figure 4

FIGURE 5

L/R RATIOS AND STRENGTH OF PLATING IN COMPRESSION (MAIN DECK)

	MAIN DECK PLATING	MAIN DECK LONGITUDINALS @ 24"	b/t	l/r	CRITICAL BUCKLING STRENGTH OF PLATING (TMB #469)	ULTIMATE COMPRESSIVE STRENGTH OF PLATING (TMB #469)	ULTIMATE COMPRESSIVE STRENGTH OF PLATING (FROM 442 CURVES)
Existing DE's	8.92	4x3x5.8# L	110	53	8800	17300	19000
	15.3	4x3x8.5# L	64	62	23800	26200	26000
	20.4	4x3x8.5# L	48	68	29900	30600	28200
DE 1006 (L/R = 50)	10.2	5x4x8.5# T	96	40	11500	19400	21000
	17.85	"	55	49	27200	28600	29900
	20.4	"	48	51	29900	30600	31300
DE 1006 (L/R = 60	10.2	5x4x5.75#T	96	44	11500	19400	21000
	17.85	"	55	58	27200	28600	28500
	20.4	"	48	60	29900	30600	29500
DE 1006 (L/R = 55)	10.2	5x4x5.75#T	96	44	11500	19400	21000
	15.3	5x4x7.5# T	64	50	23800	26200	27500
	20.4	"	48	55	29900	30600	30700

Figure 5

$$I = \frac{1}{12}\left[3A_f(d_w+t_f)^2 + 4A_w d_w^2 + 240t^4 - \frac{3(A_s d_w + A_f t_f + 60t^3)^2}{(A_s + 60t^2)}\right] \tag{18}$$

but
$$r^2 = \frac{I}{A} = \frac{I}{A_s+60t^2} \geqslant \frac{a^2}{900} \tag{19}$$

Thus
$$A_s \leqq \frac{900I}{a^2} - 60t^2 \tag{20}$$

Designing for the limit to remove the inequality sign and avoid excessive material and weight, substituting (18) into (20) we have:

$$A_s = \frac{900I}{a^2} - 60t^2 = \frac{75}{a^2}\left[3A_f(d_w+t_f)^2 + 4A_w d_w^2 + 240t^4 - \frac{3(A_s d_w + A_f t_f + 60t^3)^2}{(A_s + 60t^2)}\right] - 60t^2$$

Expanding and using order-of-magnitude arguments this expression can be reduced to the form:

$$A_s = \left[\frac{1}{18}A_s d_w t_f + \frac{1}{27}A_w d_w^2\right] + \left[\frac{5}{3}\frac{A_f}{A_s}t^2(d_w+t_f)^2 - 60t^2\right] = f_1(\text{geometry}) + f_2(t^2) \tag{21}$$

Thus $A_s = f_1$ (geometry of section) $+ f_2(t^2)$ (22)

but $t^2 = \dfrac{c_1 f(L)(1-\mu^2)}{5.75E} b^2$ whence $f_2(t^2) = f_d\left[\dfrac{(1-\mu^2)c_1 f(L)}{5.75E}\right]$ (23)

Leaving the expression for A_s in functional form and assuming that f_1 (geometry) can be expressed exclusively of t^2 and that $f_2(t^2)$ will be a direct function of t^2 with no odd powers of t (such as by substituting an average or acceptable value of A_f/A_s into the expression for A_s above) then we can write the weight equation and operate on it.

$$\gamma = \frac{\text{weight of plate + weight of stiffener}}{\text{web frame spacing x longitudinal spacing}} = \rho\left[b\left(\frac{t}{b}\right) + \frac{A_s}{b}\right] \tag{7}$$

Substituting (15) and (22) into (7):

$$\Upsilon = \rho\left\{b\left[\frac{(1-\mu^2)c_1\, f(L)}{5.75E}\right]^{1/2} + \frac{1}{b}f_1\,(\text{geometry}) + \frac{1}{b}f_2\left[\frac{b^2(1-\mu^2)c_1\, f(L)}{5.75E}\right]\right\} \tag{24}$$

Differentiating to obtain the rate of change:

$$\frac{\partial\Upsilon}{\partial\rho} = b\left\{\left[\frac{(1-\mu^2)c_1\, f(L)}{5.75E}\right]^{1/2} + \frac{1}{b}\, f_1\,(\text{geometry}) + f_2\left[\frac{b(1-\mu^2)c\, f(L)}{5.75E}\right]\right\} \tag{25}$$

$$\frac{\partial\Upsilon}{\partial E} = -\frac{\rho b}{2}\left\{\left[\frac{(1-\mu^2)c\, f(L)}{5.75E^3}\right]^{1/2} + \frac{\partial}{\partial E}\, f_2\left[\frac{b(1-\mu^2)c_1\, f(L)}{5.75E}\right]\right\} \tag{26}$$

$$\frac{\partial\Upsilon}{\partial\mu} = -\rho\, b\mu\left[\frac{c_1 f(L)}{5.75E(1-\mu^2)}\right]^{1/2} + \frac{1}{b}\frac{\partial}{\partial\mu}\, f_2\left[\frac{b(1-\mu^2)c_1\, f(L)}{5.75E}\right] \tag{27}$$

Thus, for an instability design the rate of change of structural weight varies directly with ρ (which was also true for the yield case and which we would expect), varies with E inversely as something greater than $\frac{1}{2E^{3/2}}$ and varies with μ as something greater than $\frac{\mu}{(1-\mu^2)^{1/2}}$. For comparative purposes assume that it is possible to achieve a 10% change in E, μ and ρ. Then also assume that $f_2\left[\frac{b^2(1-\mu^2)c_1\, f(L)}{5.75E}\right]$ behaves to a close degree as $c_5 \times \frac{b^2(1-\mu^2)c_1\, f(L)}{5.75E}$ so that

$$\frac{\partial\Upsilon}{\partial E} \approx -\frac{1}{E^{3/2}} \quad \text{and} \quad \frac{\partial\Upsilon}{\partial\mu} \approx -\frac{2\mu}{(1-\mu^2)^{1/2}}$$

Then a change of 10% would result in the following percentage rates of change of structural weight for aluminum and steel:

Material	E	E'	$\delta\gamma$	ρ	ρ'	$\delta\gamma$	μ	μ'	$\delta\gamma$
Steel	30×10^6	33×10^6	neg.	0.285	0.256	10%	0.30	0.33	11.1%
Aluminum	10×10^6	11×10^6	neg.	0.098	0.088	10%	0.33	0.36	11.03%

Because of the large value of E, the rate of change of weight savings is negligible for changes in value of the modulus of elasticity, but the rates of change for changes in density and Poisson's ratio appear to be comparable.

To obtain an idea of the effect of a change in one of the three previously-mentioned parameters on the structural weight itself, it is necessary to make some assumptions about the stiffener sizing. For purposes of simplicity assume that the stiffener weight is some fraction of the plating weight or of the total weight and then operate on the plating weight. In the Ship Structures Committee report by Lewis and Gerard [17], Gerard states that an optimum design would have some 47% of the material weight in the longitudinals, 33% in the plating and 20% in the web frames. If we accept this as an optimum distribution of material and neglect the web frame weight, we would find that we would have 58.75% of the material in the longitudinals and 41.75% of the material in the plating.

Then weight of stiffeners = k_1(weight of plating) and we can calculate the weight variation in the plating with a variation in mechanical properties of the material and assume that the total weight will vary in the same proportion.

Then $$\frac{\text{weight of plating}}{\text{unit area}} = \frac{\rho tab}{ab} = \rho t = \rho b\left[\frac{c_1 f(L)(1-\mu^2)}{5.75E}\right]^{1/2}$$

For variations in modulus of elasticity, density and

Poisson's ratio of 10%, the corresponding variations in weight/unit area of bottom structure will vary approximately as shown below.

Material	E	E'	$\delta \gamma$	ρ	ρ'	$\delta \gamma$	μ	μ'	$\delta \gamma$
Steel	30×10^6	33×10^6	4.81%	0.285	0.256	10%	0.30	0.33	2.09%
Aluminum	10×10^6	11×10^6	5.05%	0.098	0.088	10%	0.33	0.36	2.36%

Thus the best way to obtain a weight savings would be to reduce the density of the material while maintaining the same physical properties. The next most advantageous change lies in increasing the modulus of elasticity, other values remaining the same. The possible advantages of beryllium are markedly apparent here because beryllium combines a higher modulus with a lower density. At this stage of development, however, consideration of beryllium is solely of academic interest for reasons of scarcity, cost and difficulty of fabrication [20] and [23].

For practical purposes, then, the changes in materials which may be expected to influence the midship section design in the near future are increasing yield strengths of steel and the increasing use of aluminum. As noted by Getz [12], however, there are several other material properties which may be of as great or greater design importance than those mentioned earlier. These properties include toughness (notch sensitivity), coefficient of thermal expansion and endurance limit. His rational approach also stresses the fact that welding eccentricities, stress concentrations, built-in stresses and dynamic loadings may alter the design approach to the extent that the

traditionally-accepted static loading mechanical properties we have considered earlier are of diminished (though rarely minor) importance.

The dynamic loading problem can be of some concern also. Getz mentions that impact or dynamic loadings can amount to more than 100% of the design stress although values of 20%-50% are more typical [12]. Lewis and Dalzell in [18] in testing a destroyer model found that the measured bending moment was about 90% of the design bending moment in the sagging condition due to the ship's own wave pattern which indicated the decided effect of the ship's own wave pattern on the structural loading. They also found that the midship bending moment approached the L/20 static value for speeds below 15 knots and exceeded it for speeds greater than 15 knots in irregular seas. They also found that the vibratory effects of the seas added 40%-70% to the wave bending loads and that at a speed length ratio of 1.25 the combined wave bending and vibratory moment was 65% greater than the static moment. One of the most significant findings was that the combined vibratory and hogging or sagging moments <u>occasionally</u> exceeded the calculated value at <u>all</u> forward speeds. Furthermore, Korvin-Kroukovsky [14] has tabulated the factors affecting bending moments in waves and also assembled the results of a number of works on the dynamic effects of the sea on the ship, all of which indicate the increased moment due to dynamic effect.

In the section on slamming, Korvin-Kroukovsky expresses the ratio of true bending moment to static bending moment by the formula

$$\frac{T_1^{\,2}}{T_1^{\,2}-T^2} \qquad (28)$$

where T_1 ≡ period of wave encounter

T ≡ natural period of vibration of the ship

From the same reference the expression for maximum bending moment for a free-free beam is approximated by

$$M_{max} = \frac{4}{\pi}\,(p \times \tau)\,\frac{L}{T} \qquad (29)$$

where p ≡ load

τ ≡ duration of loading

x ≡ length over which the load is applied

L ≡ length of ship

T ≡ natural period of the ship

From both the equation for the ratio of true to static bending moment and the free-free beam approximation of the maximum midship section bending moment, it can be seen that an increase in the natural frequency of the ship will reduce the dynamic effects augmenting the midship section bending moment. Material properties can effect this for the natural period of a ship can be expressed as

$$T = 2\pi\sqrt{\frac{I_{yy} + I_y}{\rho_f\, g \nabla\, GM_L}} \qquad (30)$$

where

I_y ≡ mass moment of inertia of ship about the transverse axis

I_{yy} ≡ moment of inertia of virtual mass of water entrapped with the ship about the transverse axis

ρ_f ≡ density of fluid medium

g ≡ acceleration of gravity

∇ $\equiv$ displacement volume

GM_L $\equiv$ longitudinal metacentric radius

Thus the use of a material of high yield, different density or higher modulus of elasticity which will reduce the value of ∇ will result in a higher natural frequency for the ship and hence a lower moment. The maximum deflection (or flexure) of a ship is inversely proportional to the product of the modulus of elasticity of the material used and the moment of inertia of the midship section as given by

$$\delta_s = \iint_{-L/2}^{+L/2} \frac{M_{\text{\char"A4}}}{E I_{\text{\char"A4}}} \, dx \, dx \tag{31}$$

Ships built of high yield steels (which could afford a larger σ_l value and hence a lower $I_{\text{\char"A4}}$ value) would be prone to greater flexure in a seaway and, by virtue of their reduced stiffness, would also be more easily excited toward resonance. The same thing would be true for a ship of a material such as aluminum with its lower modulus of elasticity value. The value of high yield steel comes into its own, however, in submarine construction where increasing depth requirements cause a corresponding increase in shell thickness and weight until a depth limitation is met at the point where the hull structural weight becomes excessive unless a weight savings is effected through the use of steel or other material of increasingly great yield stress.

With the effects of the various material parameters in mind, we may now proceed to investigate the effect of using a high yield steel in place of mild steel for the bottom structure of a ship.

CHAPTER II

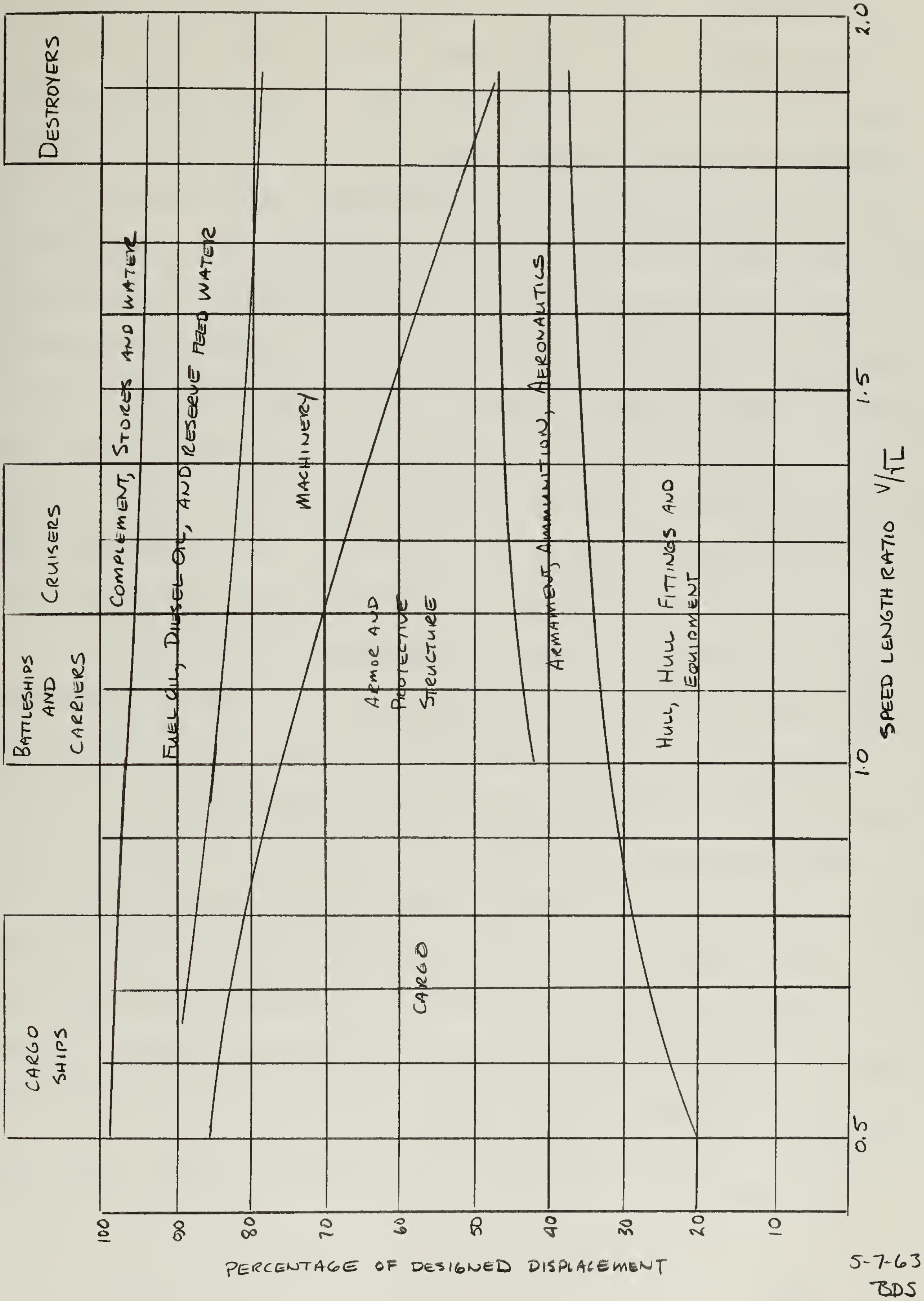
STRUCTURAL MODEL AND YIELD DESIGN CONSIDERATIONS

The goal of a structural engineer is to design a structure which will be adequate for the task which it must perform and at the same time be the least possible weight and cost. Although the least-weight design may not necessarily be the least-cost design for reasons such as increased material, fabrication and maintenance costs, it is certainly a goal of great interest even though it may serve only as basis of comparison between other designs. In the case of a ship, the midship section indicates the structural arrangement required to carry the maximum duty imposed by the sea and a reduction in midship section scantlings indicates similar reductions proceeding fore and aft from midships and hence an overall weight savings. From figure 6 we can see that the weight of hull and hull fittings and equipment can run as great as some 37.5% of the design displacement which indicates that a reduction in hull structural weight may result in an increased payload or reduced powering requirement of a significant degree.

When considering the midship section, the main strength (and weight) members are the web frames, the longitudinals and, of course, the shell plating. The shell plating is designed on the basis of the head of water it must resist, the aspect ratio of the panel as determined by the web frame and longitudinal spacing, and the expected σ_1 stress. The longitudinals serve to support the shell plating, acting as

THE EFFECT OF VARIATION IN SPEED ON USEFUL LOAD

FIGURE 6



transverse boundaries for the plate panels, and in general are sized to resist a given ship girder (σ_1) stress without buckling or tripping. The combination of plating and longitudinal is generally sized so as to meet a limiting slenderness ratio depending upon its distance from the neutral axis of the midship section neutral axis. The web frames serve as longitudinal boundaries for the plating panels and provide transverse strength to the side shell. They are sized based on the circumferential (or transverse) bending moment around the girth of the ship. These three structural members combine to form a large percentage of the hull structural weight, and changes in size or arrangement of any of them will affect the design and weight of the hull structure.

In order to approach the problem of minimizing the hull structural weight, it is convenient to have a yardstick with which one can determine the relative merit of each design. In [10] and [11] Gerard advances the idea of "solidity" which he defines as the ratio of the cross-sectional area of the structural members to the area circumscribed by the structural member. For example, if the total cross-sectional area of the structural members of the midship section of a ship of beam B, depth D and midship section coefficient $C_{\text{⊗}}$ is A, then its solidity is expressed as $\frac{A}{C_{\text{⊗}} BD}$. This, however, is not a very good standard of comparison for different designs because

1. It does not incorporate the effect of a change in construction material weight between two designs.

2. The solidity ratio will probably be a very small number and changes in the solidity value are liable to be obscured.

3. No longitudinal effects are included.

4. Weight is more important than cross-sectional area.

A more representative means of comparison would be to calculate the weight per unit area (length and breadth) of the bottom structure because:

1. This would incorporate the longitudinal (stringer) and transverse (web frame) effects.

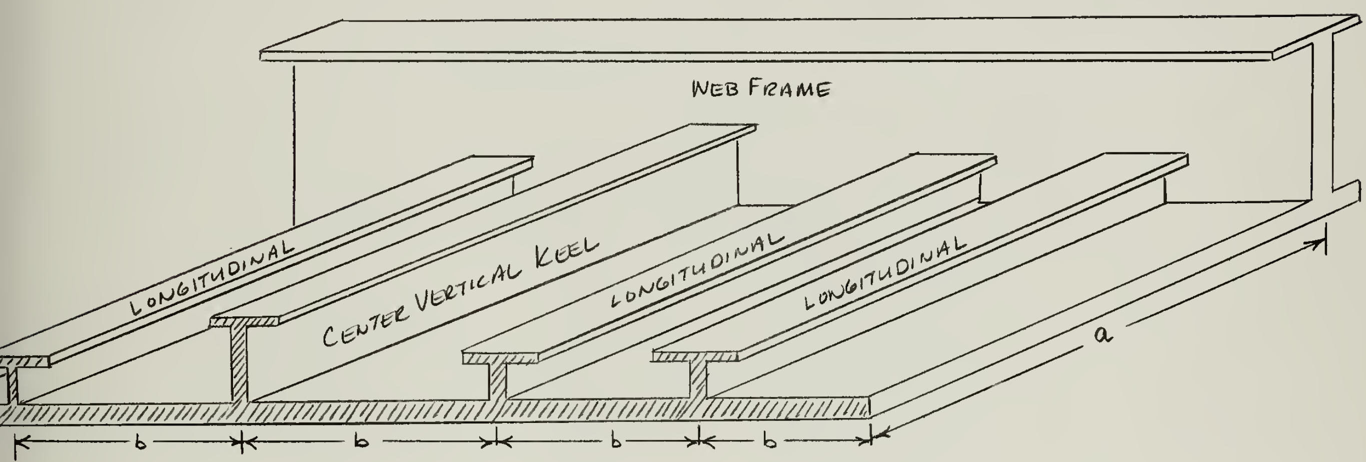
2. A change in weight would be more readily apparent although, because bottom weight will vary due to a change in the depth of ship, we shall have to assume that the depth of the model varies as the draft of the model, thus implying a free board which is independent of length for simplifying reasons.

3. The bottom structure is the heaviest region (per unit area) of the midship section and therefore possibly of greatest initial interest.

Aircraft designers use a reference figure of weight of aircraft divided by wing area to indicate the amount of lift required per unit area of wing as one of their design comparison figures. The use of bottom structural weight per unit area of bottom is somewhat comparable to this. Let us then define such a figure of comparison as structural specific weight and denote it by the symbol γ as used in the preceding chapter. Theoretically it would be at its most useful for the case of ships of large $C_{\text{⊠}}$ where the deadrise angle

is small and the bottom strength requirement (and hence structural weight) is uniform over a comparatively large transverse distance.

From figures 7 and 8 we can see the three different stresses that must be considered in the bottom structural design as outlined by Professor Evans in [8] . A typical section of the bottom structure is as shown below:



a ≡ web frame spacing b ≡ longitudinal spacing

Considering the panel of plating of dimensions a x b lying between two longitudinals and two web frames, the stresses acting on it will be as shown:

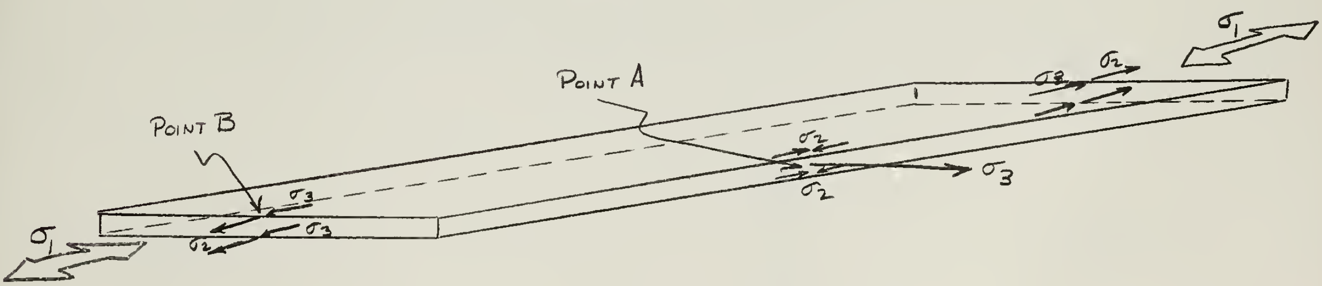


FIGURE 7

BENDING STRESSES IN SHIPS BOTTOM

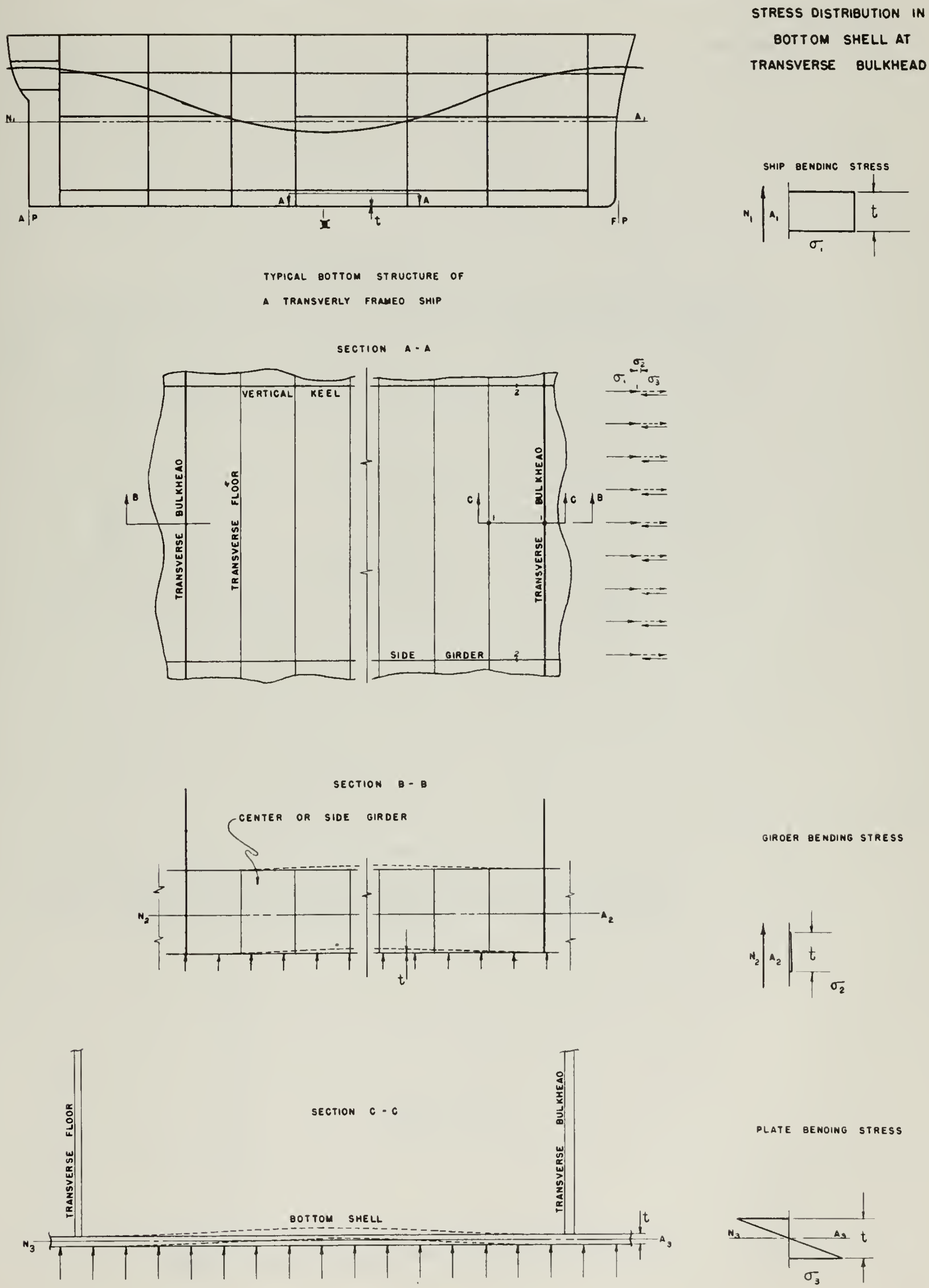
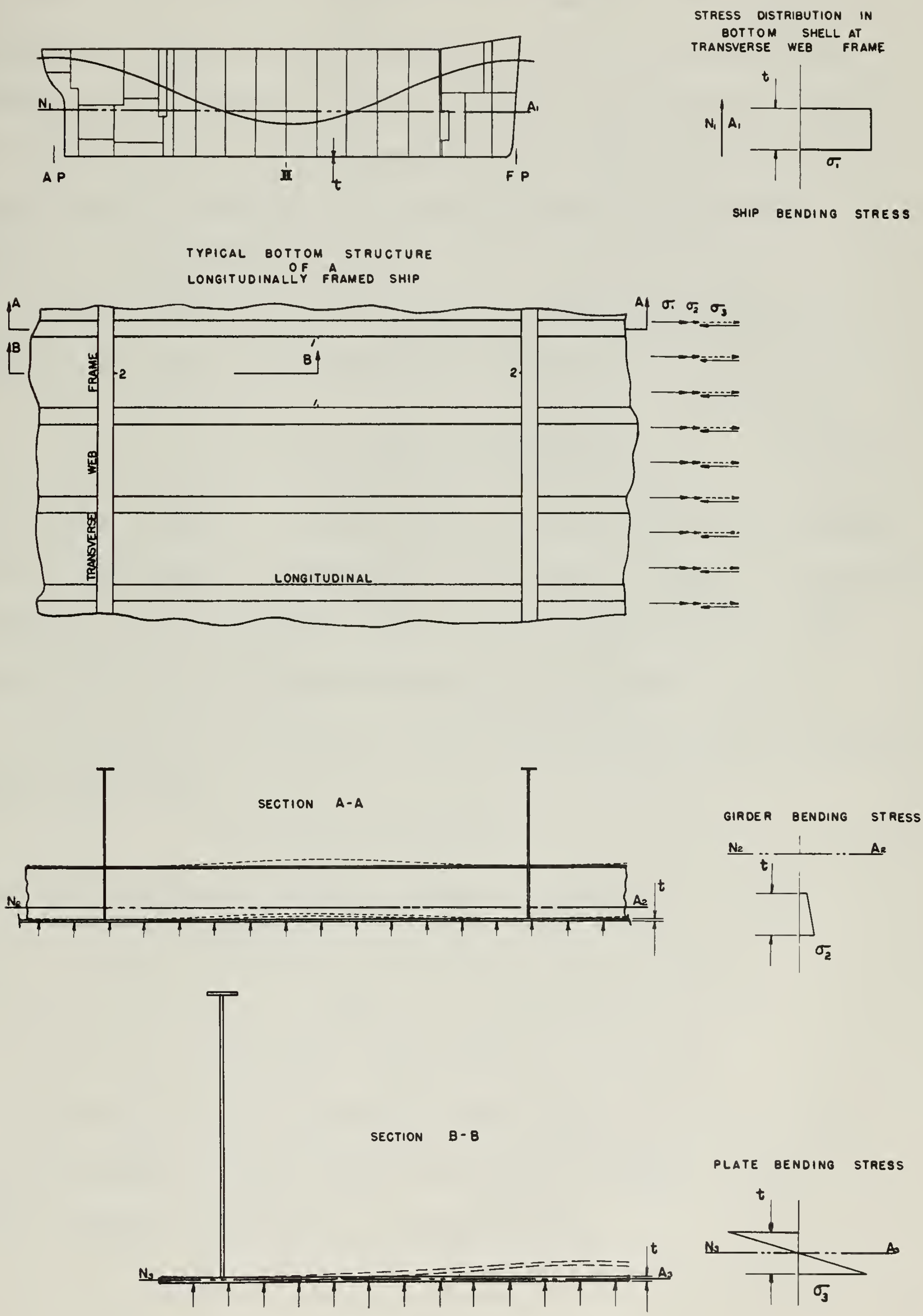


FIGURE 8

BENDING STRESSES IN SHIPS BOTTOM



Assuming a longitudinal spacing value and a web frame spacing value (for which the a/b ratio is generally >1.6), obtaining a σ_1 value from the length of ship using the Tobin or other criterion (see figure 9), assuming a constant positive σ_2 value on the order of 1 T/in^2 and knowing the value of yield strength of the material one generally finds two minimum values of σ_3 from the four cases - one for the inner plating (hogging condition) and one for the outer plating (sagging condition).

These values for σ_3 are then substituted in the expression for the bottom plating as given by:

$$\sigma = \sigma_3 = \frac{1}{2} k \rho H \left(\frac{b}{t}\right)^2 \frac{1}{144} \tag{3}$$

as shown in figure 1, which allows a solution for the bottom plating thickness. The value of the head of water, H, will be different for the hogging case and the sagging case - the maximum value of plating thickness being chosen.

Now $\sigma_y \geq \pm \sigma_1 + \sigma_2 \pm \sigma_3$. For the outer plating, sagging condition we have

$$\pm \sigma_y \geqslant \sigma_1 + \sigma_2 + \sigma_3$$

while for the inner plating, hogging condition, we have

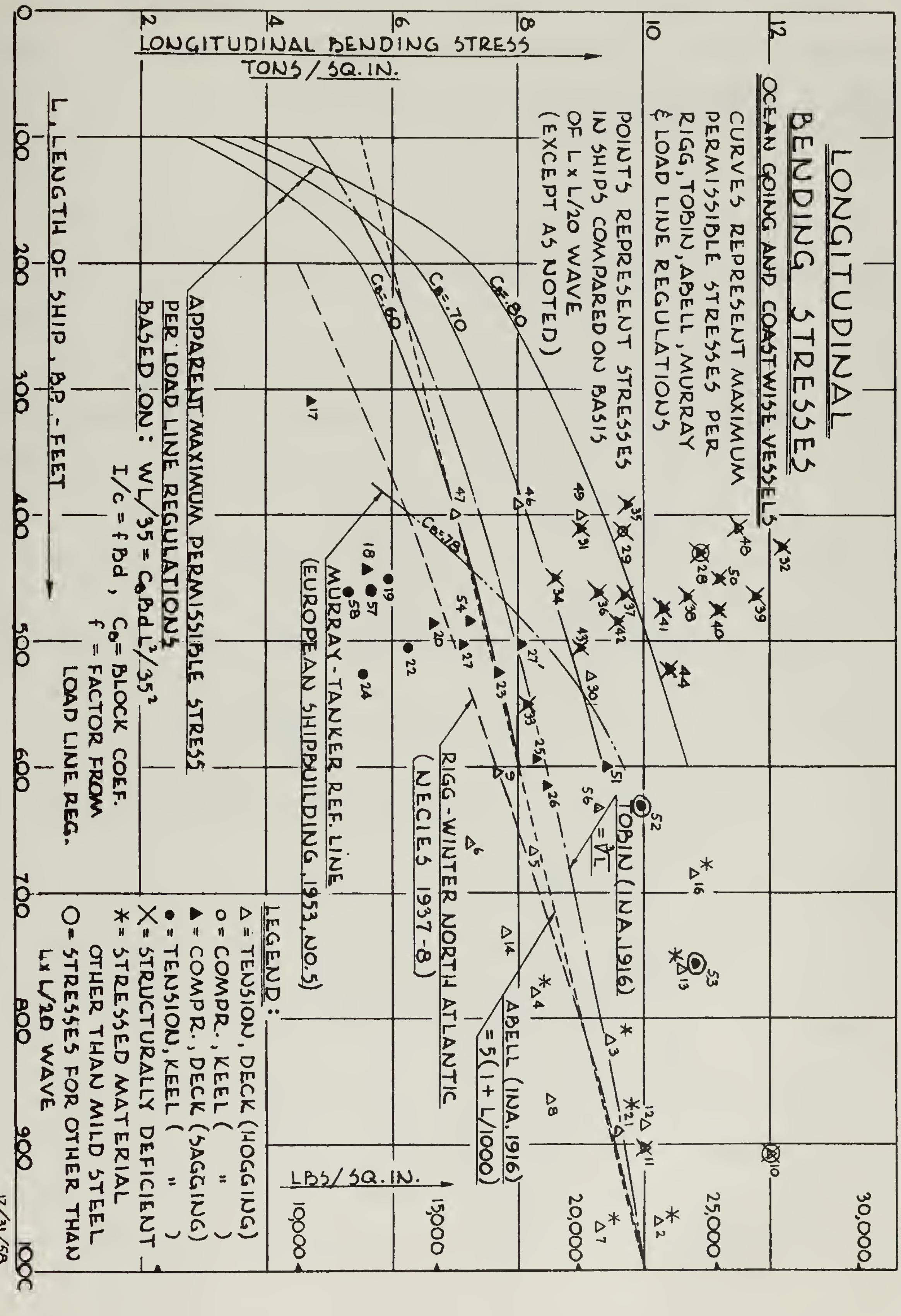
$$-\sigma_y \geqslant -\sigma_1 + \sigma_2 - \sigma_3$$

or

$$\sigma_y \geqslant \sigma_1 - \sigma_2 + \sigma_3$$

The difference between the two cases lies in the difference in head of water and difference in sign of the stress (whether additive or subtractive).

FIGURE 9


LONGITUDINAL BENDING STRESSES
OCEAN GOING AND COASTWISE VESSELS
CURVES REPRESENT MAXIMUM PERMISSIBLE STRESSES PER RIGG, TOBIN, ABELL, MURRAY & LOAD LINE REGULATIONS
POINTS REPRESENT STRESSES IN SHIPS COMPARED ON BASIS OF L x L/20 WAVE (EXCEPT AS NOTED)
LONGITUDINAL BENDING STRESS TONS/SQ.IN.
L, LENGTH OF SHIP, B.P. - FEET
LBS/SQ.IN.
10,000
15,000
20,000
25,000
30,000
APPARENT MAXIMUM PERMISSIBLE STRESS PER LOAD LINE REGULATIONS
BASED ON: WL/35 = $C_B B d L^2/35$
I/c = f B d, C_B = BLOCK COEF.
f = FACTOR FROM LOAD LINE REG.
C_B=.60
C_B=.70
C_B=.80
C_B=.78
MURRAY-TANKER REF. LINE
(EUROPEAN SHIPBUILDING, 1953, NO.5)
RIGG-WINTER NORTH ATLANTIC
(NECIES 1937-8)
TOBIN (INA, 1916)
$= \sqrt[3]{L}$
ABELL (INA, 1916)
$= 5(1 + L/1000)$
LEGEND:
Δ = TENSION, DECK (HOGGING)
o = COMPR., KEEL (")
▲ = COMPR., DECK (SAGGING)
● = TENSION, KEEL (")
X = STRUCTURALLY DEFICIENT
* = STRESSED MATERIAL OTHER THAN MILD STEEL
O = STRESSES FOR OTHER THAN L x L/20 WAVE
12/31/58

Consider the case of the outer plating, sagging condition for which $\sigma_y \geq \sigma_1 + \sigma_2 + \sigma_3$.

As an estimate for σ_1 let us take the value obtained by Khoushy [13] which he obtained by modifying the Tobin criterion for a 1/16" wastage allowance since $\frac{Z(\text{wastage allowance} = 1/16")}{Z(\text{load line regulations})} = 2.4L^{-0.10}$.

Then $\sigma_1 = 2.4L^{0.23}$ T/in^2

Other values for the variation of σ_1 with L are shown in figure 9.

Experience has shown that the σ_2 value can be reasonably approximated by a constant stress on the order of one ton per square inch. Therefore, let

$$\sigma_2 = 1.0 \ T/in^2$$

Then $\sigma_3 = \frac{1}{2} \frac{k \rho H}{144} (\frac{b}{t})^2 lb/in^2$ (3)

which for sea water and expressed in tons/in^2 becomes

$$\sigma_3 = \frac{1}{10,080} kH \left(\frac{b}{t}\right)^2 \qquad (32)$$

With no factor of safety, then, we have:

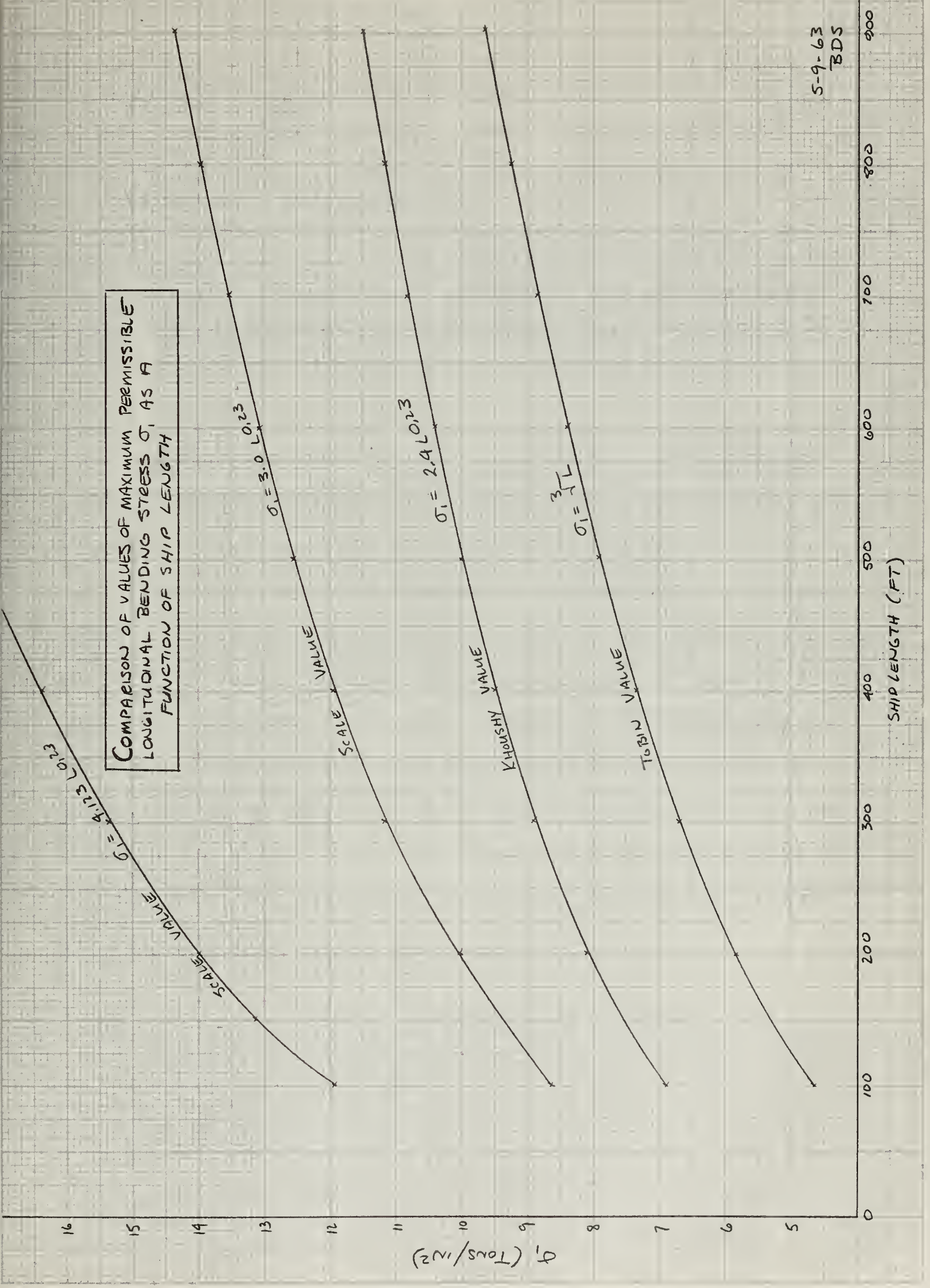
$$\sigma_y \geq 2.4L^{0.23} + 1.0 + \frac{kH}{10,080} \left(\frac{b}{t}\right)^2 \qquad (33)$$

Re-arranging and solving for "b" we find:

$$b \leq 100.4t \left[\frac{\sigma_y - 2.4L^{0.23} - 1.0}{kH}\right]^{1/2} \qquad (34)$$

For aspect ratios from a/b = 1.0 to a/b > 1.6 we find values of k from 0.618 to 0.685. Using the chart from figure 1 we can obtain the correct value of k_B, take the square root, remove it from the radical and re-write the expression for b as

FIGURE 9(a)



COMPARISON OF VALUES OF MAXIMUM PERMISSIBLE LONGITUDINAL BENDING STRESS σ_1 AS A FUNCTION OF SHIP LENGTH
SCALE VALUE
$\sigma_1 = 4.123\ L^{0.23}$
SCALE VALUE
$\sigma_1 = 3.0\ L^{0.23}$
KHOUSHY VALUE
$\sigma_1 = 2.4\ L^{0.23}$
TOBIN VALUE
$\sigma_1 = \sqrt[3]{L}$
σ_1 (TONS/IN²)
5
6
7
8
9
10
11
12
13
14
15
16
SHIP LENGTH (FT)
0
100
200
300
400
500
600
700
800
900
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BDS

$$b \leq Ct \left[\frac{\sigma_y - 2.4L^{0.23} - 1.0}{H} \right]^{1/2} \qquad (35)$$

where $C = \dfrac{100.4}{\sqrt{k_B}}$

Values of C are as follows:

a/b	1.0	1.20	1.25	1.30	1.35	1.40	1.45	1.50	1.55	1.60
K_B	0.618	0.665	0.670	0.675	0.679	0.681	0.682	0.683	0.684	0.685
$K_B^{1/2}$	0.7861	0.8155	0.8185	0.8216	0.8241	0.8252	0.8258	0.8264	0.8270	0.827
C	127.72	123.11	122.66	122.20	121.83	121.67	121.58	121.49	121.40	121.31

One may now solve for "b" as a function of the length of ship, maximum head of water above the bottom plating, yield strength of the material and plating thickness.

Since the plating thickness is a function of the aspect ratio of the panel, the yield strength of the material and the head of the water, however, an initial value of plating thickness must be chosen. To choose values of "t" we can assume web frame spacings (and thus values of "a"), determine t/b values for given values of H, σ_y and a/b ratios and then convert the t/b value to the t/a value using the given value of "a" and solve for t directly as a function of H, σ_y, a and a/b ratio. These values are as follows:

H	σ_y	t/b (a/b=1)	t a=48"	t a=96"	t/b (a/b=1.2)	t a=48"	t a=96"	t/b (a/b=1.4)	t a=48"	t a=96"	t/b (a/b=1.6)	t a=48"	t a=96"
10	15.6	0.00605	0.290	0.580	0.00625	0.300	0.600	0.00645	0.310	0.620	0.0066	0.317	0.634
	26.8	0.00475	0.228	0.456	0.00485	0.233	0.466	0.00495	0.238	0.476	0.00505	0.2425	0.485
15	15.6	0.0075	0.360	0.720	0.00767	0.368	0.736	0.00783	0.376	0.752	0.0080	0.384	0.768
	26.8	0.00575	0.276	0.552	0.00583	0.280	0.560	0.00592	0.284	0.568	0.0060	0.288	0.576
20	15.6	0.0089	0.4275	0.855	0.0091	0.437	0.874	0.0093	0.447	0.894	0.0095	0.456	0.912
	26.8	0.0065	0.312	0.624	0.00668	0.321	0.642	0.00686	0.330	0.660	0.00705	0.3385	0.677

H	σ_y	t/b (a/b=1)	t a=48"	t a=96"	t/b (a/b=1.2)	t a=48"	t a=96"	t/b (a/b=1.4)	t a=48"	t a=96"	t/b (a/b=1.6)	t a=48"	t a=96"
25	15.6	0.00995	0.4775	0.955	0.00998	0.480	0.960	0.0101	0.484	0.968	0.0105	0.504	1.008
	26.8	0 0075	0.360	0.720	0.00767	0.368	0.736	0.00783	0.376	0.752	0.008	0.384	0.768
30	15.6	0.01075	0.515	1.03	0.01093	0.525	1.05	0.1111	0.533	1.067	0.0113	0.542	1.084
	26.8	0.00805	0.387	0.774	0.0082	0.394	0.788	0.00835	0.401	0.802	0.0085	0.408	0.816

One can then follow an iterative process of assuming an a/b ratio, choosing a value "t", solving for "b" (using the appropriate value of C) and checking the resulting a/b ratio against the assumed a/b ratio. If they agree, the assumed value of "t" was correct and the value of "b" will be correct. If they do <u>not</u> agree, one must enter with a new assumed value of a/b (preferably the previously-calculated value of a/b) and follow an iterative process until the assumed and the calculated values of a/b agree.

Values of "b" have been determined for the cases considered which include:

1. Web frame spacings of 48" and 96"
2. Heads from 10' to 30' in 5' increments
3. Ship lengths from 300' to 900' in 200' increments
4. Yield strengths of 15.6 T/in^2 (35,000 lb/in^2) and 26.8 T/in^2 (60,000 lb/in^2).

With the given values of "b" and the known aspect ratios of the plate, one can then test the plate to determine at what critical stress it will fail through instability by means of the Bryan formula:

$$\sigma_{cr} = \frac{k\pi^2 E}{12(1-\mu^2)} \left(\frac{t}{b}\right)^2 \qquad (2)$$

where the value of k depends upon the panel aspect ratio and the assumed boundary conditions. Assuming partial support to be given by the panel boundaries, we will choose the values for k from the condition assuming the "a" edges are fixed and the "b" edges are simply supported as shown in figure 3.

Having determined values of σ_{cr} we can now test and see whether the panel scantlings chosen on a basis of not exceeding the yield strength of the material will also be sufficient to withstand a buckling stress of the magnitude of the hull girder stress σ_1 determined by the original estimate:

$$\sigma_1 = 2.4L^{0.23}$$

If the σ_1 stress exceeds the σ_{cr} value, the panel will buckle and the design is insufficient. If the σ_1 stress is less than the σ_{cr} stress, it may be assumed that the critical stress will never be reached and that the design on the yield basis is satisfactory.

Having obtained values of "b" one can proceed to determine values of structural specific weight for each case from the equation:

$$\gamma = \frac{\rho tab + \rho a A_s}{ab} = \frac{\rho tab + (\#/\text{ft of stiffener})\, a}{ab}$$

$$\gamma = \rho t + \frac{\#/\text{ft. of stiffener}}{b}$$

The stiffener values were chosen from the BuShips Section Modulus graphs as the lightest stiffener available for each thickness of plating for each case. This was a simplifying assumption for the "yield" design, i.e., a design not subject to buckling due to the expected σ_1 stress. The second cycle would involve checking the stiffeners and their associated plating for a σ_2 stress and then revising the stress schedule and repeating the process.

It was assumed that the stiffeners did not have to meet the limiting L/r or slenderness ratio assuming that instability would not be a problem. The values of γ were obtained for all cases (even those for which instability was expected) in order to provide not only a comparison of γ values for differing a, σ_y, L and H values but also for later comparison with designs which met the instability problem.

A similar set of values was obtained using the Tobin value

$$\sigma_1 = \sqrt[3]{L}$$

in lieu of the Khoushy value in order to compare the effects.

It was also noted that a higher value of σ_y should mean a higher allowable value of σ_1 for design purposes. For this reason two other values for σ_1 were established and the results obtained for comparative purposes.

One of these values scaled the Khoushy value for σ_1 upwards in proportion to the increase in yield strength whence

$$\sigma_1 = \left(\frac{26.8}{15.6}\right) 2.4L^{0.23} = 4.123L^{0.23}$$

The other value took an additional, arbitrary 25% increase in σ_1 which resulted in

$$\sigma_1 = 1.25\ (2.4L^{0.23}) = 3.0L^{0.23}$$

Values of b, final a/b ratio compared with estimated a/b ratio, k_c, σ_{cr}, γ and L' (length corresponding to critical stress using the design σ_1 value) may be found in appendix A.

Having obtained values for panel scantlings on the basis of ship length, head of water, yield strength of material and web frame spacing and having determined a value of ship length for which σ_{cr} was assumed to be σ_1 we can now develop an interesting plot. For each entering combination of H, L, σ_y and a, we will establish a value of L' in the following fashion.

$$\sigma_1 = 2.4L^{0.23}$$

$$\therefore \quad L^{0.23} = \frac{\sigma_1}{2.4}$$

$$L' = \left(\frac{\sigma_1}{2.4}\right)^{4.35} = \left(\frac{\sigma_{cr}}{2.4}\right)^{4.35} \qquad (36)$$

Values of L' for the Tobin and other criteria for σ_1 can be developed the same way.

Then, having values for L' one can plot values of L' against H_{max} for each entering value of L. Where $L > L'$ one can expect that the length of ship is such that a value of $\sigma_1 > \sigma_{cr}$ will be developed and failure will occur through instability of the bottom structure.

For values of $L < L'$ it can be assumed that the ship is short enough in comparison to its draft that a critical value of σ_1 will never be developed.

To determine the transition from yield to instability failure, one merely has to enter the family of curves at a given value of L' and follow the ordinate to the point where it intersects the curve for the corresponding value of L. Transition occurs at L = L', i.e., $\sigma_l = \sigma_{cr}$. By connecting those points of intersection (L = L') for a family of ship lengths, one develops a curve which marks the transition from yield to instability failure. For those values of H above the line the bottom plating will be sufficiently thick (based on the head requirement) to insure a stable panel subject to the loading and boundary conditions assumed. For those values below the line, the plating will be so thin as to allow failure by panel instability before the expected value of σ_l or σ_{cr} is reached.

Values of H_{max} vs. L' are given for the four different σ_l criteria in figures 10-13, and a comparison of the shapes of the transition curves for the four criteria is given in figure 14.

A design which fails through instability is an inefficient design because the full strength of the material is not utilized. Since for an optimum design $\sigma_{cr} = \sigma_y$ it is necessary to add additional material to the structure to raise the σ_{cr} value to the σ_y value, and this causes the instability design to have a heavier γ value than the yield design. With respect to figures 10-13, then, the optimum design procedure would be to design a ship of a given length such that it lies on or above the transition line in the yield domain. For ships of higher yield steel (where the

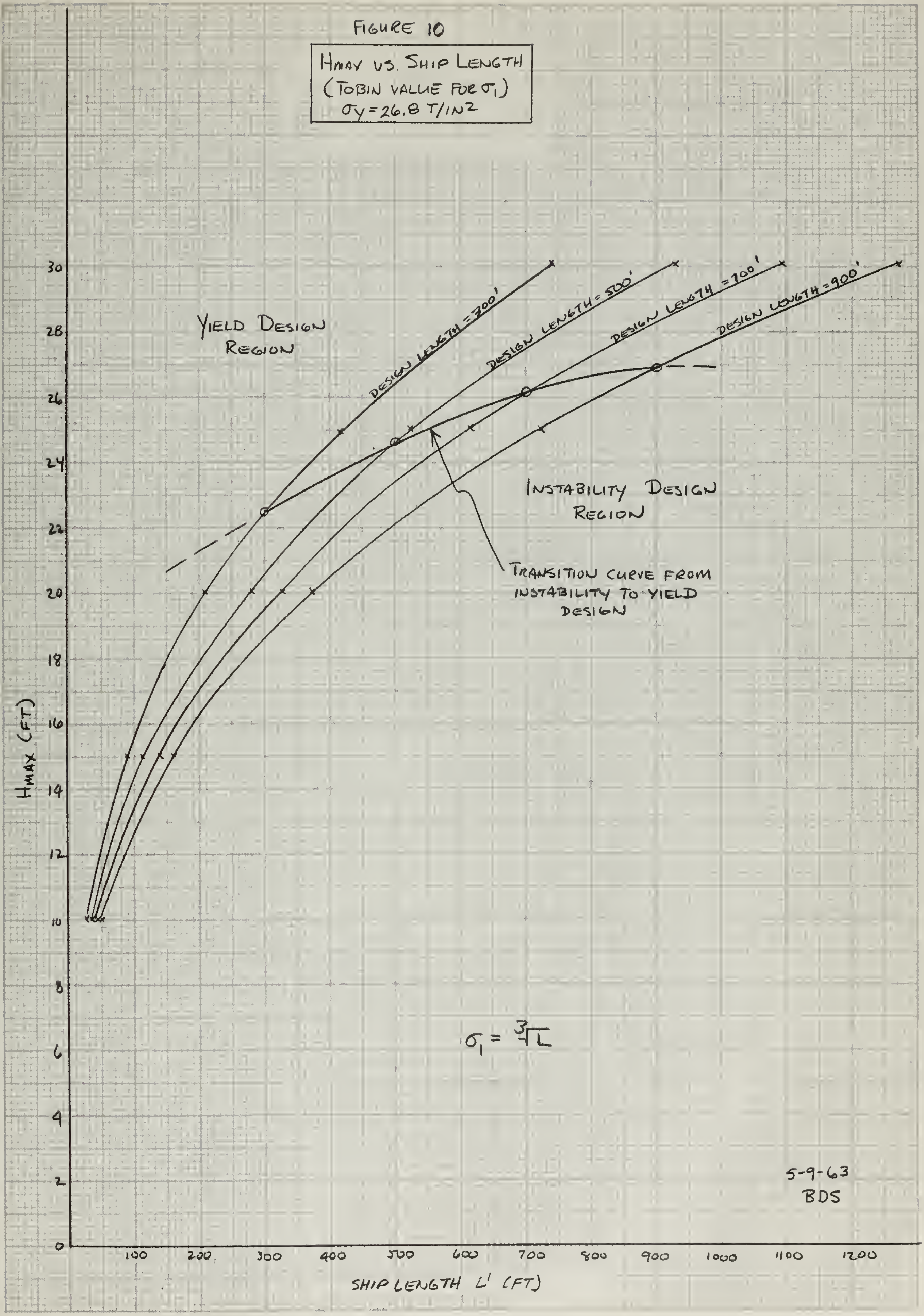
FIGURE 10
HMAX VS. SHIP LENGTH
(TOBIN VALUE FOR σ_1)
$\sigma_y = 26.8$ T/IN²
YIELD DESIGN REGION
DESIGN LENGTH = 300'
DESIGN LENGTH = 500'
DESIGN LENGTH = 700'
DESIGN LENGTH = 900'
INSTABILITY DESIGN REGION
TRANSITION CURVE FROM INSTABILITY TO YIELD DESIGN
$\sigma_1 = \sqrt[3]{L}$
HMAX (FT)
SHIP LENGTH L' (FT)
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BDS

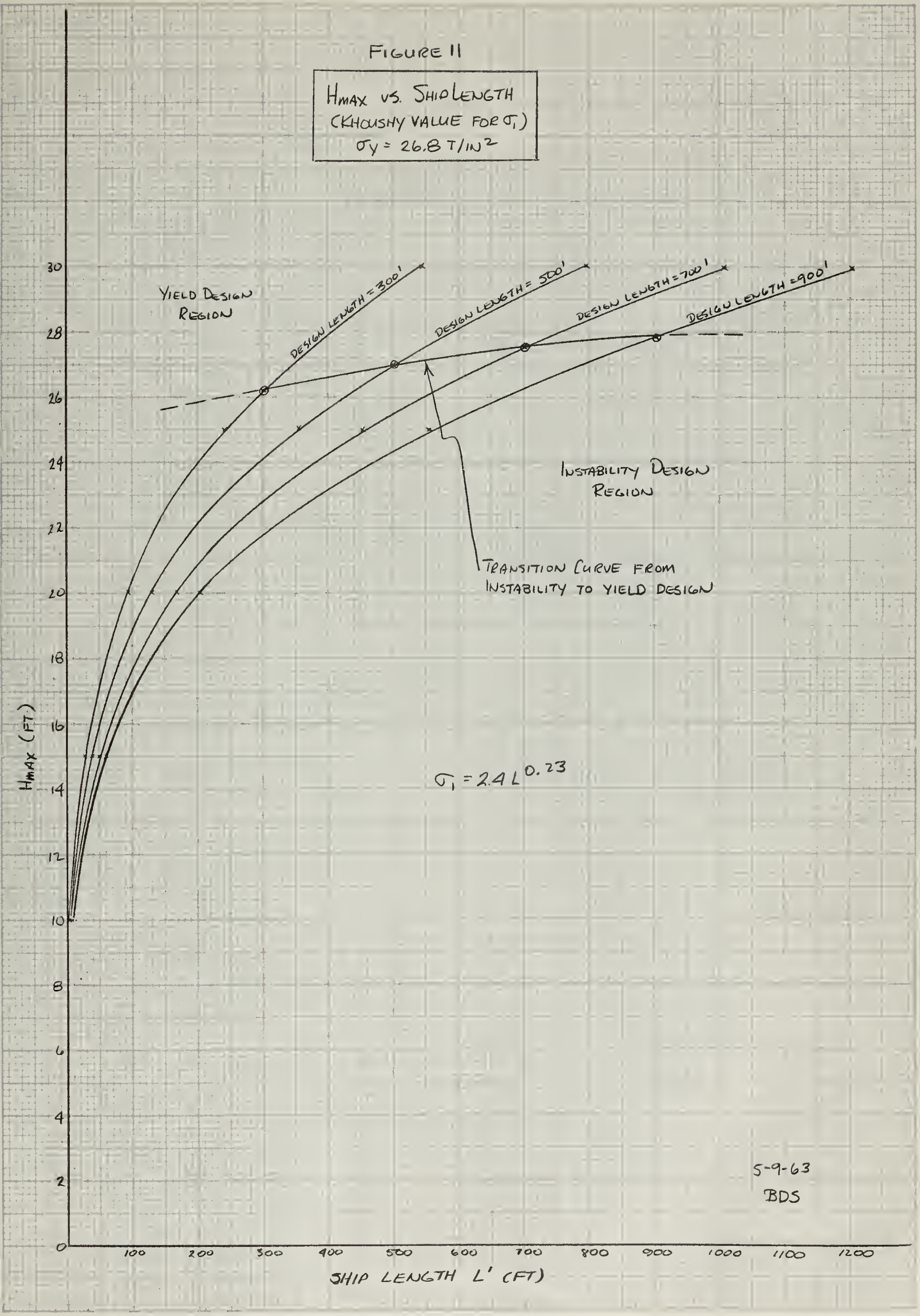
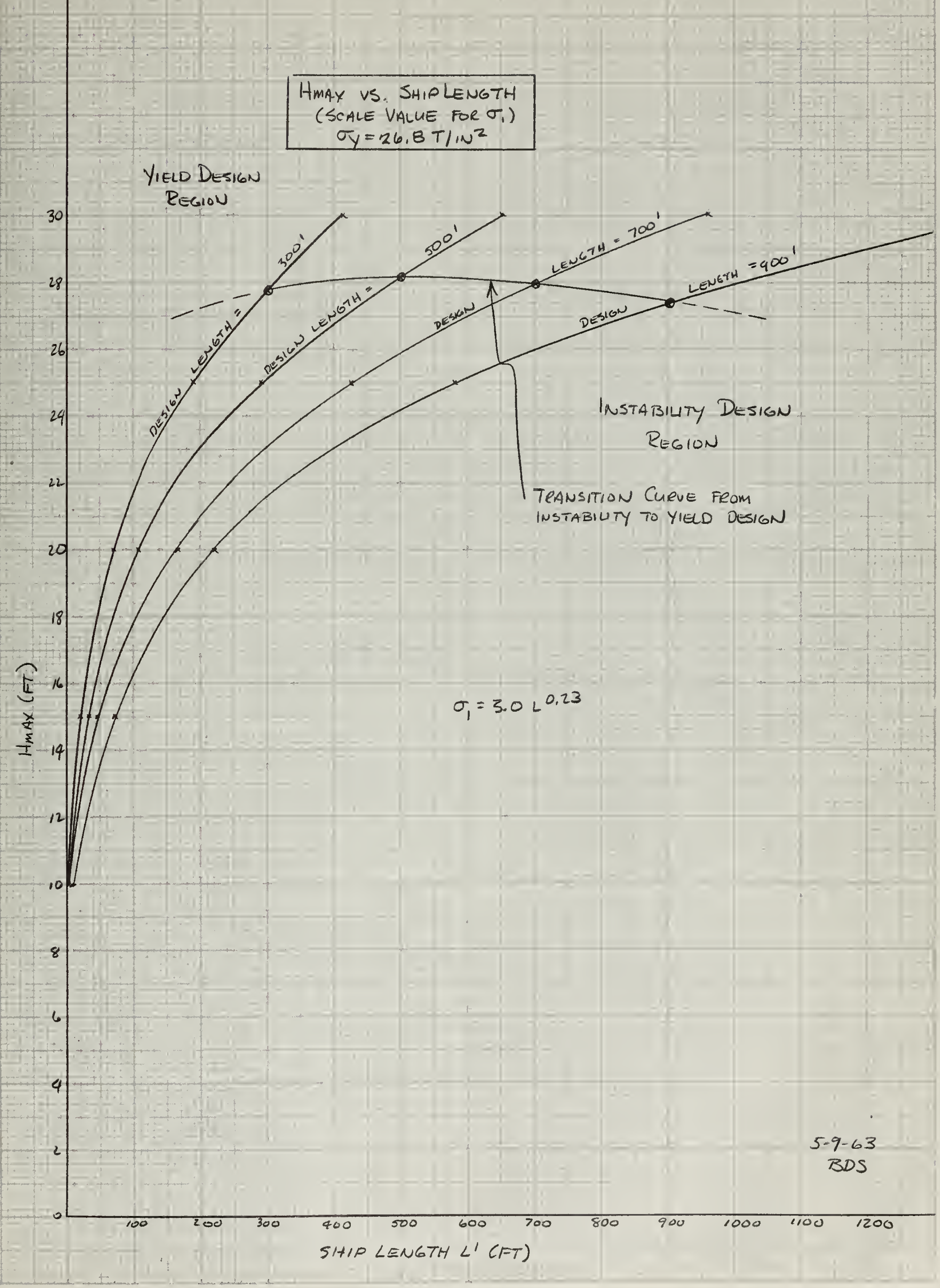


FIGURE 11
HMAX VS. SHIP LENGTH
(KHOUSHY VALUE FOR σ_1)
$\sigma_y = 26.8\ T/IN^2$
YIELD DESIGN REGION
DESIGN LENGTH = 300'
DESIGN LENGTH = 500'
DESIGN LENGTH = 700'
DESIGN LENGTH = 900'
INSTABILITY DESIGN REGION
TRANSITION CURVE FROM INSTABILITY TO YIELD DESIGN
$\sigma_1 = 2.4\ L^{0.23}$
HMAX (FT.)
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
100
200
300
400
500
600
700
800
900
1000
1100
1200
SHIP LENGTH L' (FT)
5-9-63
BDS

FIGURE 12


HMAX VS. SHIP LENGTH
(SCALE VALUE FOR σ_1)
$\sigma_y = 26.8\ T/IN^2$
YIELD DESIGN REGION
DESIGN LENGTH = 300'
DESIGN LENGTH = 500'
DESIGN LENGTH = 700'
DESIGN LENGTH = 900'
INSTABILITY DESIGN REGION
TRANSITION CURVE FROM INSTABILITY TO YIELD DESIGN
$\sigma_1 = 3.0\ L^{0.23}$
HMAX (FT.)
SHIP LENGTH L' (FT)
5-9-63
BDS

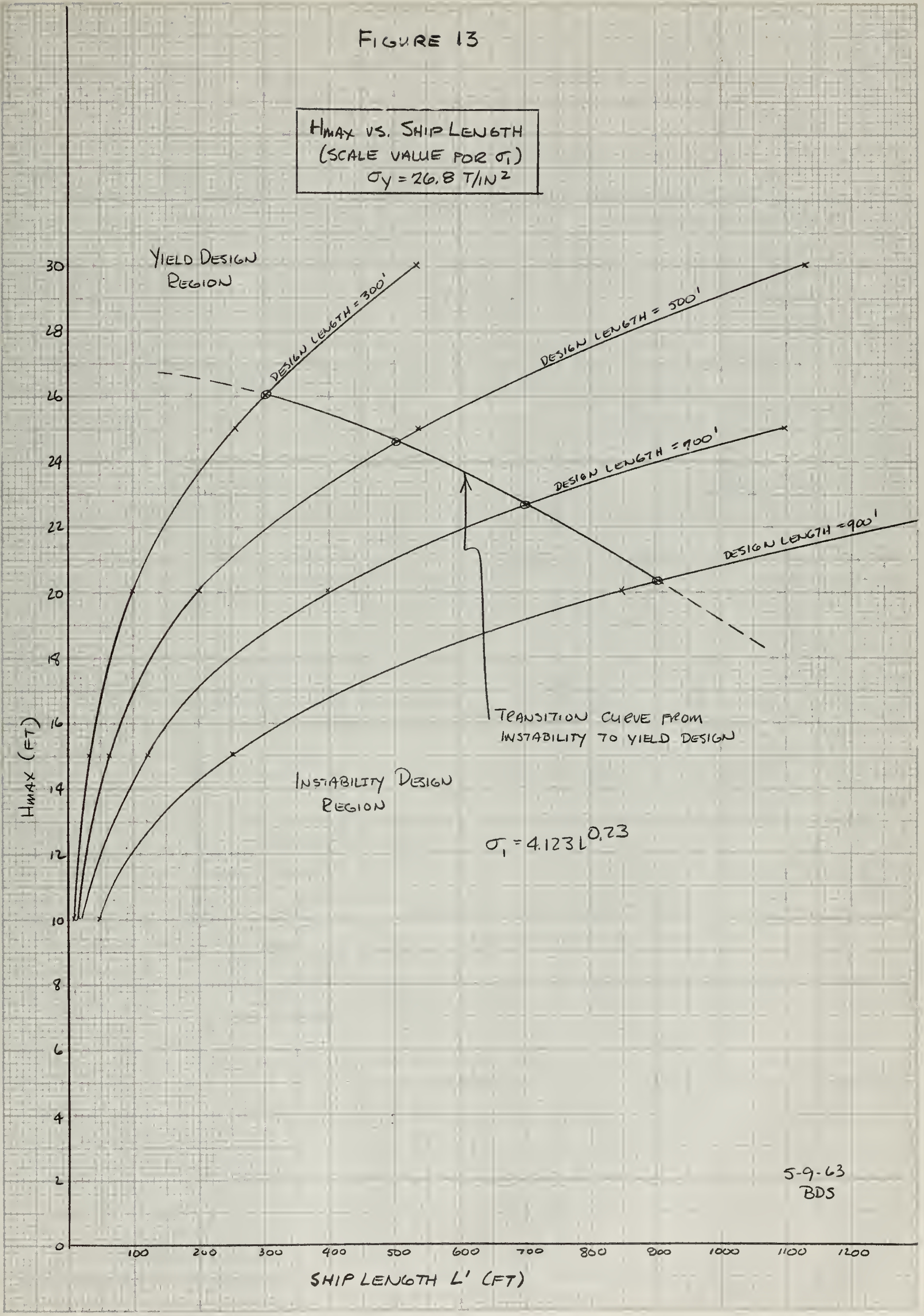
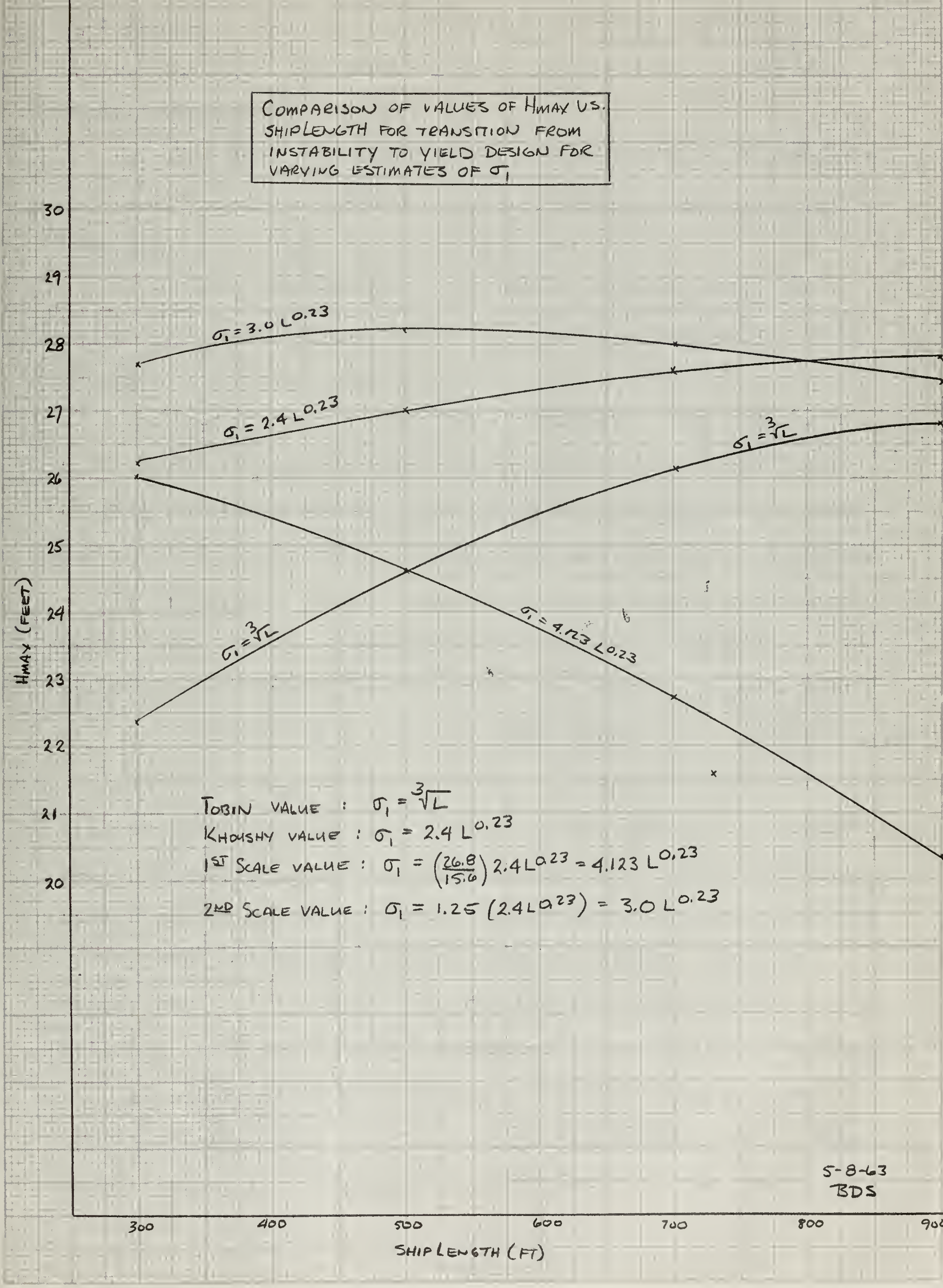


FIGURE 13
HMAX VS. SHIP LENGTH
(SCALE VALUE FOR σ_1)
$\sigma_y = 26.8\ T/IN^2$
YIELD DESIGN REGION
DESIGN LENGTH = 300'
DESIGN LENGTH = 500'
DESIGN LENGTH = 700'
DESIGN LENGTH = 900'
TRANSITION CURVE FROM INSTABILITY TO YIELD DESIGN
INSTABILITY DESIGN REGION
$\sigma_1 = 4.123 L^{0.23}$
HMAX (FT)
SHIP LENGTH L' (FT)
5-9-63
BDS

FIGURE 14


COMPARISON OF VALUES OF HMAX VS. SHIPLENGTH FOR TRANSITION FROM INSTABILITY TO YIELD DESIGN FOR VARYING ESTIMATES OF σ_1
$\sigma_1 = 3.0\,L^{0.23}$
$\sigma_1 = 2.4\,L^{0.23}$
$\sigma_1 = \sqrt[3]{L}$
$\sigma_1 = 4.123\,L^{0.23}$
$\sigma_1 = \sqrt[3]{L}$
TOBIN VALUE : $\sigma_1 = \sqrt[3]{L}$
KHOUSHY VALUE : $\sigma_1 = 2.4\,L^{0.23}$
1ST SCALE VALUE : $\sigma_1 = \left(\frac{26.8}{15.6}\right) 2.4L^{0.23} = 4.123\,L^{0.23}$
2ND SCALE VALUE : $\sigma_1 = 1.25\,(2.4L^{0.23}) = 3.0\,L^{0.23}$
HMAX (FEET)
20
21
22
23
24
25
26
27
28
29
30
300
400
500
600
700
800
900
SHIP LENGTH (FT)
5-8-63
BDS

bottom plating will be thinner than for lower yield steels) this suggests that the midship section design could be modified in at least two ways to reduce the effects of the instability problem:

1. Maximize the draft to as great an extent as possible to require that the bottom plating, sized on local hydrostatic loading, will support a higher critical stress.

2. Raise the strength deck to the highest level possible to obtain the maximum section modulus value for a ship of given proportions and thus lower the σ_1 value.

The use of a high yield steel under the same standards as mild steel would be impractical because the closer longitudinal spacing required would increase the fabrication cost and greatly reduce the weight savings that could be effected.

A comparison of the three standards for σ_1 as evidenced by the plots of the transition curve shows a change in gradient with length from positive for Tobin to almost zero for $\sigma_1 = 3.0L^{0.23}$ to a negative gradient for $\sigma_1 = 4.123L^{0.23}$.

One would expect the gradient to remain positive for a well-designed ship, i.e., the greater the length the greater the σ_1 value and hence the greater the draft required to insure that the bottom plating would be of sufficient thickness to support the critical stress without failure. On this basis, the $\sigma_1 = 4.123L^{0.23}$ expression for σ_1 is clearly artificial and the $3.0L^{0.23}$ criterion is subject to question.

An interpretation of the $\sigma_1 = 4.123L^{0.23}$ transition curve indicates that for increasing ship lengths the σ_1 value becomes excessive, dominating the stresses to the extent that

the σ_3 value allowed is so small that the bottom plating becomes excessive, capable of carrying a σ_{cr} stress far in excess of σ_1. It is also doubtful that the midship section scantlings under such a condition would be so light as to allow so great a stress.

An interpretation of the $\sigma_1 = 3.0L^{0.23}$ stress indicates a relative insensitivity to length in the 300'-700' length region followed by the same behavior as the preceding criterion for lengths in excess of 700'. While arguments have been advanced for a constant, uniform design value for σ_1 independent of length, actual stresses as shown in figure 9 indicate the trend toward a σ_1 increase with length.

The optimum value of σ_1 for a least-weight design is a minimum value since this maximizes the σ_3 value allowed and hence reduces the bottom shell plating thickness requirements. This will be shown in Chapter III where the increase in γ with expected σ_1 value is apparent, the Tobin values resulting in a least-weight solution each time.

The final judge of the efficiency of any σ_1 criterion will, of course, be the design of a ship or of a number of ships for a new yield strength material followed by a comparison on a length basis of the actual σ_1 values involved. That a higher σ_1 value for a high yield steel than for a mild steel should be allowed seems advisable, since use of the mild steel value for σ_1 in conjunction with a standard stress schedule would allow σ_3 values of such magnitude as to almost certainly always result in an instability failure of the bottom panel plating on the first design cycle due to the

reduced thickness. It would seem that values between $\sigma_1 = 2.4L^{0.23}$ and $\sigma_1 = 3.0L^{0.23}$, with the latter as an upper limit, would bear further investigation.

Once an optimum value of σ_1 has been decided upon and a transition curve that corresponds to "real-life" conditions has been developed, the optimum design would be for a ship whose design parameters cause it to fall on the line, thus assuming that $\sigma_1 = \sigma_{cr}$.

It must be stressed at this point that the model which has been developed is used to illustrate a procedure and is not intended to act as an actual design tool at this time. This is due to the fact that

1. This considers only one of the two critical cases - a second set of curves should also be developed for the investigation of the inner plating, hogging condition.

2. Values of H or H_{max} are for the head of water above the keel in the sagging condition for this model, i.e., the value of H for which the bottom plating is designed. This is not the draft except for the still-water case.

3. The values of σ_1 and σ_2 are only estimates. This limits the approach to the first cycle of the design iterative process.

4. No factor of safety has been incorporated.

The advantages of the model lie in the fact that the results serve as an estimate of stringer spacings for given values of the other parameters and that the development of the model for the inner plating, hogging condition involves no more than a change in sign of the σ_2 value.

In the next chapter those structures subject to instability failure will be investigated and their scantlings adjusted to provide for an adequate design in order that "final" designs (adequate for the yield or instability criteria as appropriate) may be compared on the basis of yield strength, ship length and web frame spacing as well as the γ differences between the yield and instability criteria.

CHAPTER III

INSTABILITY CONSIDERATIONS

The model just considered yielded results which were adequate from a stability point of view and also results which were inadequate and would be subject to buckling of the plate panel when subjected to the σ_1 ship girder bending stress. The latter results must be adjusted to be sufficient for a σ_{cr} value at least as great as σ_1 where

$$\sigma_{cr} = \frac{k\pi^2 E}{12(1-\mu^2)} \left(\frac{t}{b}\right)^2 \qquad (2)$$

For given boundary conditions and aspect ratio the value of k is constant. For a given type of material the values of E and μ are constant. Thus the Bryan formulation for critical stress may be expressed as

$$\sigma_{cr} = K \left(\frac{t}{b}\right)^2$$

The value of σ_{cr} can thus be adjusted by either increasing the plating thickness "t" or reducing the longitudinal spacing "b". An optimum design would seek to minimize the weight so a choice must be made as to which approach would be the better. Using partial differentiation to check the rate of change:

$$\frac{\partial \sigma_{cr}}{\partial t} = \frac{2Kt}{b^2} \qquad \frac{\partial \sigma_{cr}}{\partial b} = -\frac{2Kt^2}{b^3}$$

The plating weight being such a large percentage of the specific structural weight, the effect which would decrease the plating weight the more rapidly would be the best

parameter to vary. The rate of increase of critical stress with an increase of plating thickness is linear with t but the rate of increase of critical stress with longitudinal spacing varies inversely as the cube of the longitudinal spacing, a much more rapid increase. The better of the two ways to raise the critical stress and minimize the weight is to reduce the longitudinal spacing, and this is generally accepted procedure.

The desired item of information then is the longitudinal spacing for which the plating thickness will be adequate. One may take the expression for σ_{cr} and re-arrange it to solve for the longitudinal spacing, given the plating thickness, aspect ratio and boundary conditions. This yields

$$b^2 = \frac{Kt^2}{\sigma_{cr}}$$

The value of σ_{cr} for this case would, of course, be the σ_1 value using the same formula for σ_1 used to obtain the results for the yield case.

Here again an iterative process is required because the value of a new "b" changes the panel size and hence the aspect ratio from which the plating thickness was originally obtained. The convergence is fairly rapid but it must be noted that a failure to recognize the effect of the new panel size on the plating thickness requirement leads to errors either of excess weight or insufficient stability.

Having sized the new panel it is now necessary to consider the effect of slenderness ratio on the longitudinal-plating combination. To prevent premature buckling or

tripping of the longitudinal, it is generally accepted practice to set an upper limit on the allowable slenderness ratio of the longitudinal-plating combination. This depends on the distance from the neutral axis. There is room for argument on the limiting value as shown by the range of values in figures 3 and 4 which have proved adequate, but for purposes of illustration let us take an upper limit on slenderness ratio of 35.

Using this criterion, $a/r \leq 35$ whence $r \geq a/35$ and $r^2 \geq a^2/1225$. But $r^2 = I/A$ for the plating-longitudinal combination. One can now go into the BuShips section modulus graphs and determine the required stiffener size for a given size plating in order to meet the limiting value of slenderness ratio using an effective width of plating of 60t. Using this value of stiffener weight/foot and also the new panel size, one can determine a structural specific weight value for the structure.

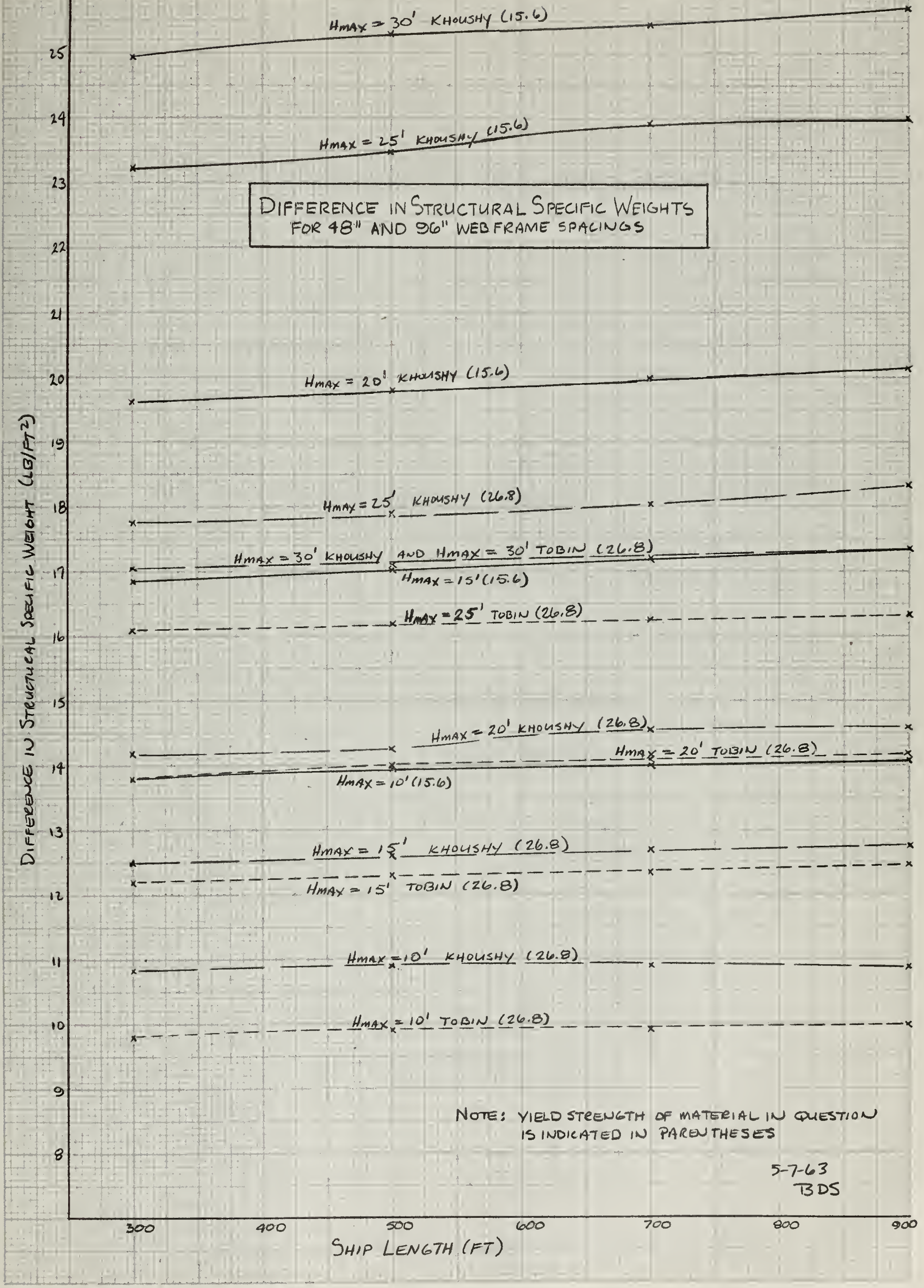
The results of the re-design on the instability requirement combined with the results of the yield requirement allow the plotting of several interesting functions of ship length. These include:

1. The difference in structural specific weights with changes in H_{max}, yield strength of material and web frame spacing for different σ_1 criteria. (Fig. 15 and 16).

2. Savings of high yield over mild steel on a percentage basis for the variations mentioned above. (Fig. 17-20).

3. Structural specific weight values for optimum L-H values lying on the transition curve for various values of

Figure 15


DIFFERENCE IN STRUCTURAL SPECIFIC WEIGHTS
FOR 48" AND 96" WEB FRAME SPACINGS
HMAX = 30' KHOUSHY (15.6)
HMAX = 25' KHOUSHY (15.6)
HMAX = 20' KHOUSHY (15.6)
HMAX = 25' KHOUSHY (26.8)
HMAX = 30' KHOUSHY AND HMAX = 30' TOBIN (26.8)
HMAX = 15' (15.6)
HMAX = 25' TOBIN (26.8)
HMAX = 20' KHOUSHY (26.8)
HMAX = 20' TOBIN (26.8)
HMAX = 10' (15.6)
HMAX = 15' KHOUSHY (26.8)
HMAX = 15' TOBIN (26.8)
HMAX = 10' KHOUSHY (26.8)
HMAX = 10' TOBIN (26.8)
NOTE: YIELD STRENGTH OF MATERIAL IN QUESTION IS INDICATED IN PARENTHESES
5-7-63
BDS
DIFFERENCE IN STRUCTURAL SPECIFIC WEIGHT (LB/FT²)
SHIP LENGTH (FT)
25
24
23
22
21
20
19
18
17
16
15
14
13
12
11
10
9
8
300
400
500
600
700
800
900

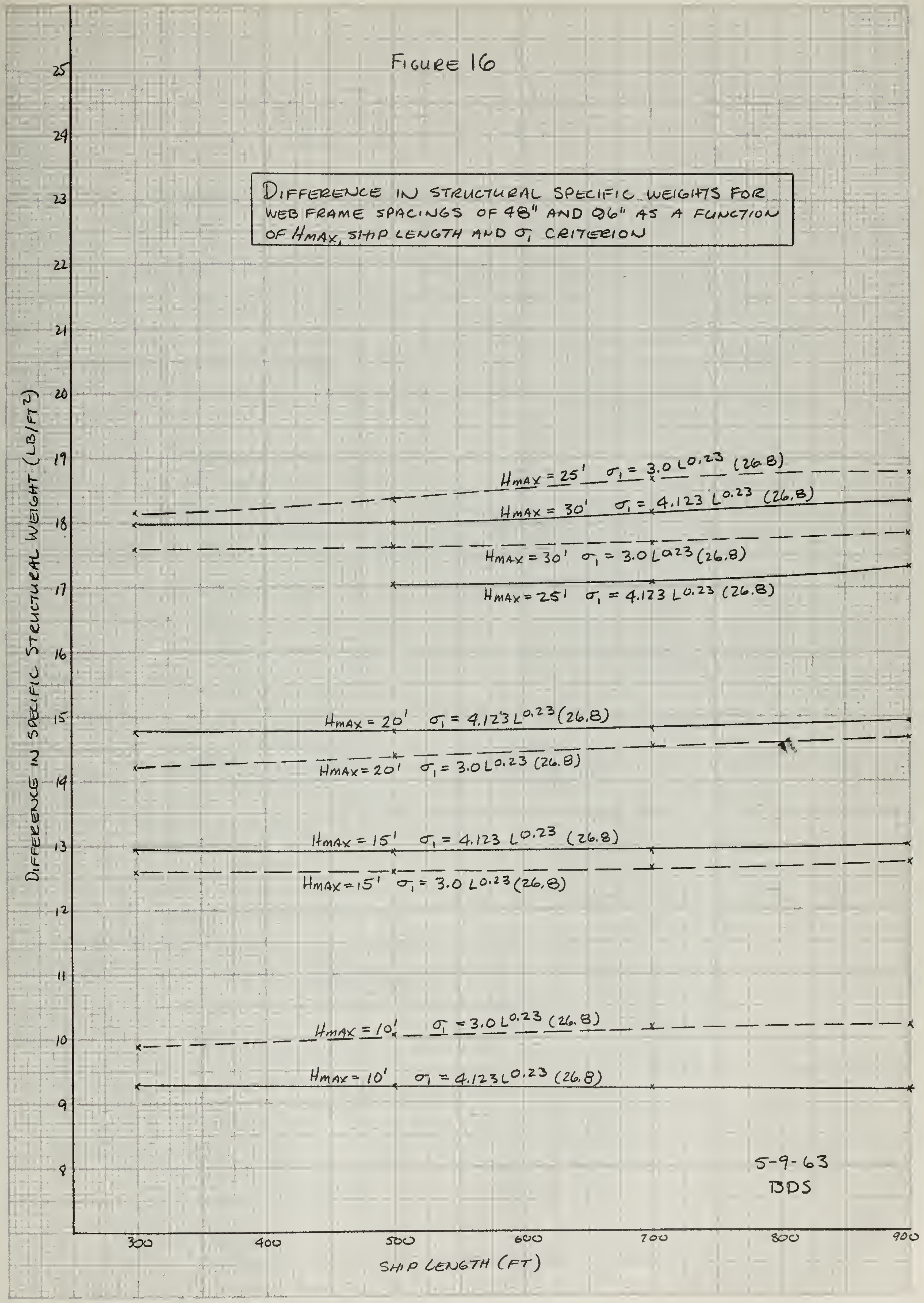


FIGURE 16
DIFFERENCE IN STRUCTURAL SPECIFIC WEIGHTS FOR WEB FRAME SPACINGS OF 48" AND 96" AS A FUNCTION OF H_{MAX}, SHIP LENGTH AND σ_1 CRITERION
$H_{MAX} = 25'$ $\sigma_1 = 3.0\,L^{0.23}$ (26.8)
$H_{MAX} = 30'$ $\sigma_1 = 4.123\,L^{0.23}$ (26.8)
$H_{MAX} = 30'$ $\sigma_1 = 3.0\,L^{0.23}$ (26.8)
$H_{MAX} = 25'$ $\sigma_1 = 4.123\,L^{0.23}$ (26.8)
$H_{MAX} = 20'$ $\sigma_1 = 4.123\,L^{0.23}$ (26.8)
$H_{MAX} = 20'$ $\sigma_1 = 3.0\,L^{0.23}$ (26.8)
$H_{MAX} = 15'$ $\sigma_1 = 4.123\,L^{0.23}$ (26.8)
$H_{MAX} = 15'$ $\sigma_1 = 3.0\,L^{0.23}$ (26.8)
$H_{MAX} = 10'$ $\sigma_1 = 3.0\,L^{0.23}$ (26.8)
$H_{MAX} = 10'$ $\sigma_1 = 4.123\,L^{0.23}$ (26.8)
DIFFERENCE IN SPECIFIC STRUCTURAL WEIGHT (LB/FT^2)
25
24
23
22
21
20
19
18
17
16
15
14
13
12
11
10
9
8
300
400
500
600
700
800
900
SHIP LENGTH (FT)
5-9-63
BDS

FIGURE 17

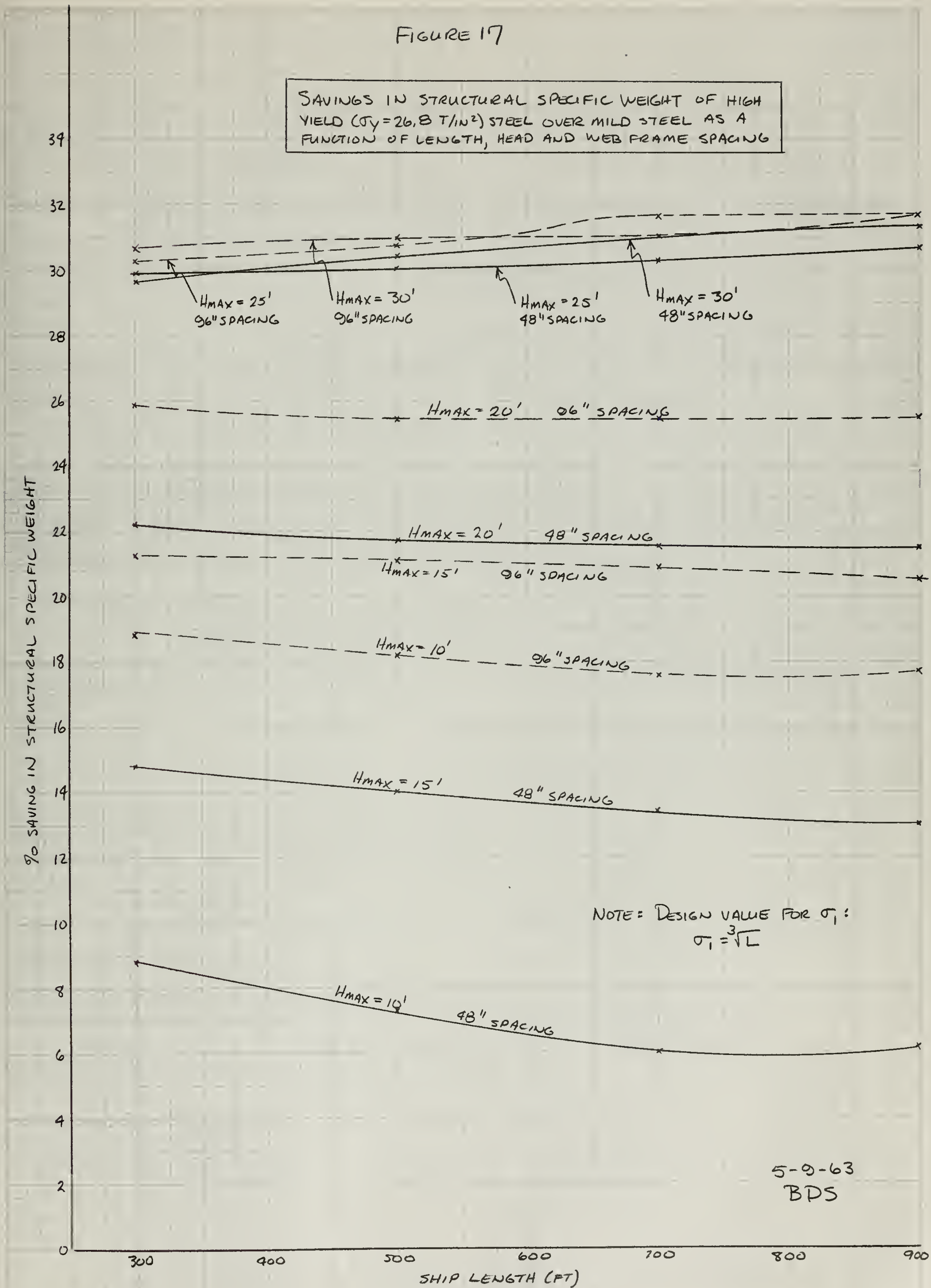
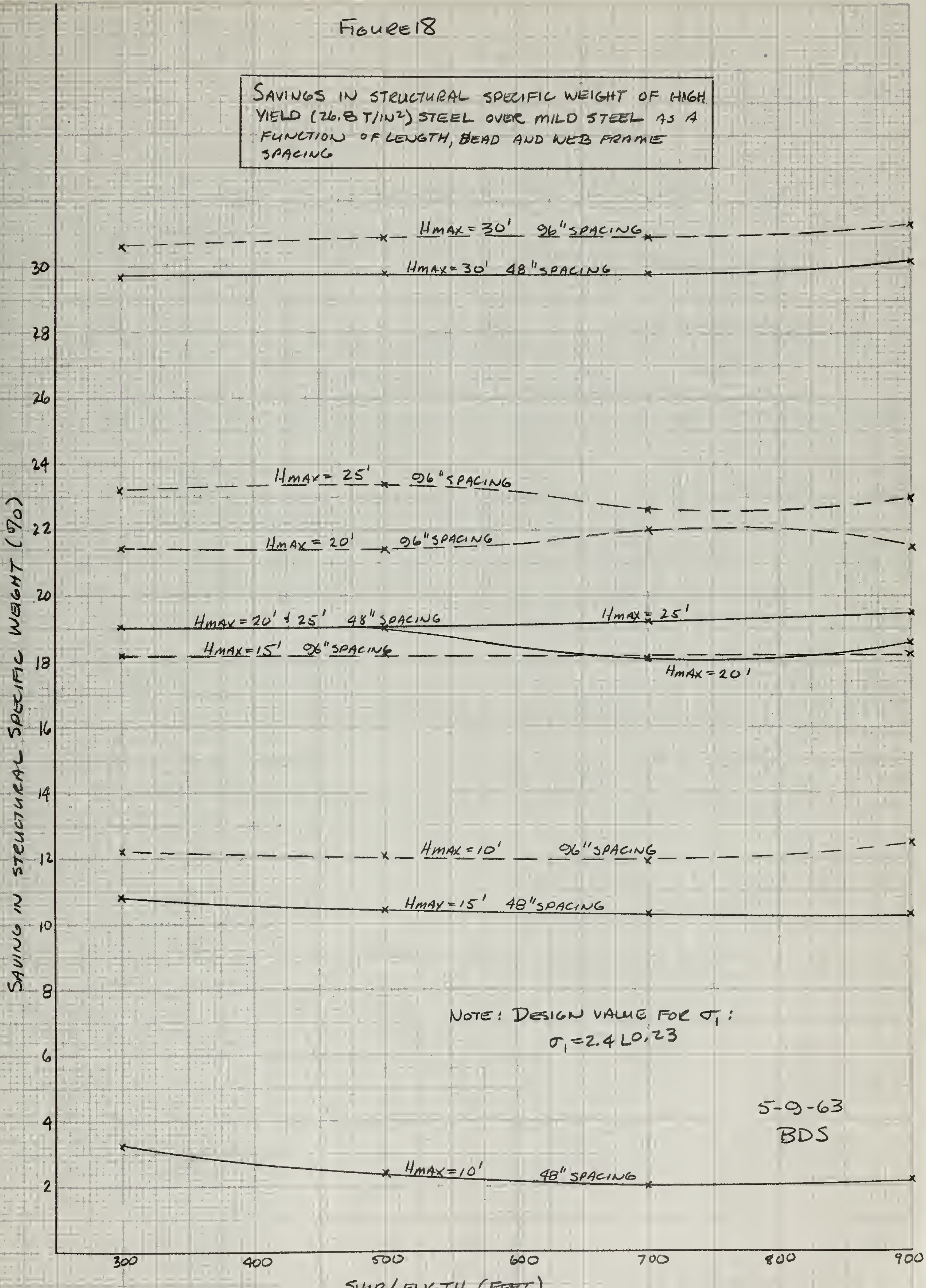

SAVINGS IN STRUCTURAL SPECIFIC WEIGHT OF HIGH YIELD (σ_y = 26.8 T/IN²) STEEL OVER MILD STEEL AS A FUNCTION OF LENGTH, HEAD AND WEB FRAME SPACING
% SAVING IN STRUCTURAL SPECIFIC WEIGHT
SHIP LENGTH (FT)
HMAX = 25' 96" SPACING
HMAX = 30' 96" SPACING
HMAX = 25' 48" SPACING
HMAX = 30' 48" SPACING
HMAX = 20' 96" SPACING
HMAX = 20' 48" SPACING
HMAX = 15' 96" SPACING
HMAX = 10' 96" SPACING
HMAX = 15' 48" SPACING
HMAX = 10' 48" SPACING
NOTE: DESIGN VALUE FOR σ_1: $\sigma_1 = \sqrt[3]{L}$
5-9-63
BDS

FIGURE 18



SAVINGS IN STRUCTURAL SPECIFIC WEIGHT OF HIGH YIELD (26.8 T/IN²) STEEL OVER MILD STEEL AS A FUNCTION OF LENGTH, HEAD AND WEB FRAME SPACING
HMAX = 30' 96" SPACING
HMAX = 30' 48" SPACING
HMAX = 25' 96" SPACING
HMAX = 20' 96" SPACING
HMAX = 20' & 25' 48" SPACING
HMAX = 25'
HMAX = 15' 96" SPACING
HMAX = 20'
HMAX = 10' 96" SPACING
HMAY = 15' 48" SPACING
HMAX = 10' 48" SPACING
NOTE: DESIGN VALUE FOR σ1: σ1 = 2.4 L0.23
5-9-63
BDS
SAVING IN STRUCTURAL SPECIFIC WEIGHT (%)
30
28
26
24
22
20
18
16
14
12
10
8
6
4
2
300
400
500
600
700
800
900
SHIP LENGTH (FEET)

FIGURE 19

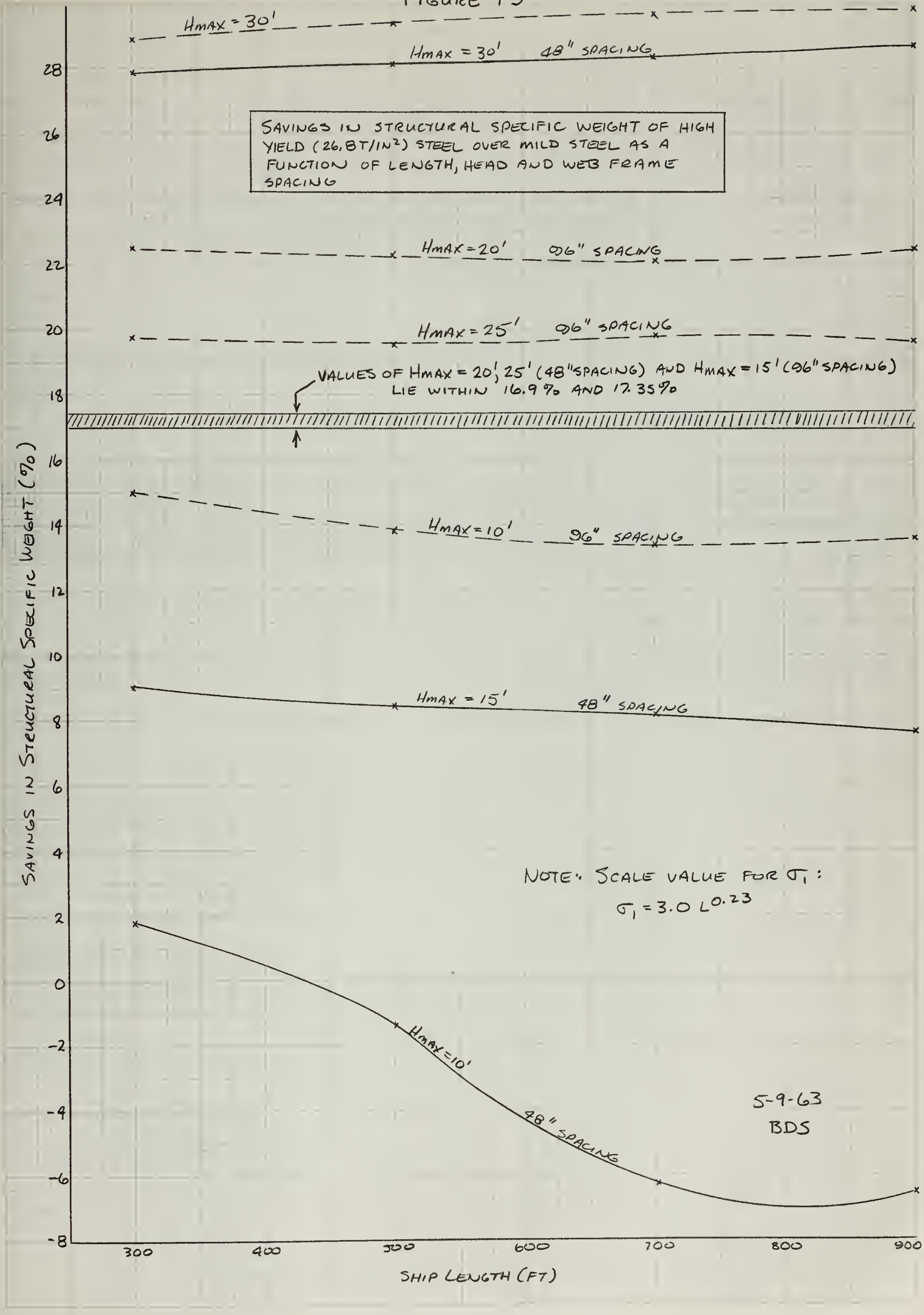
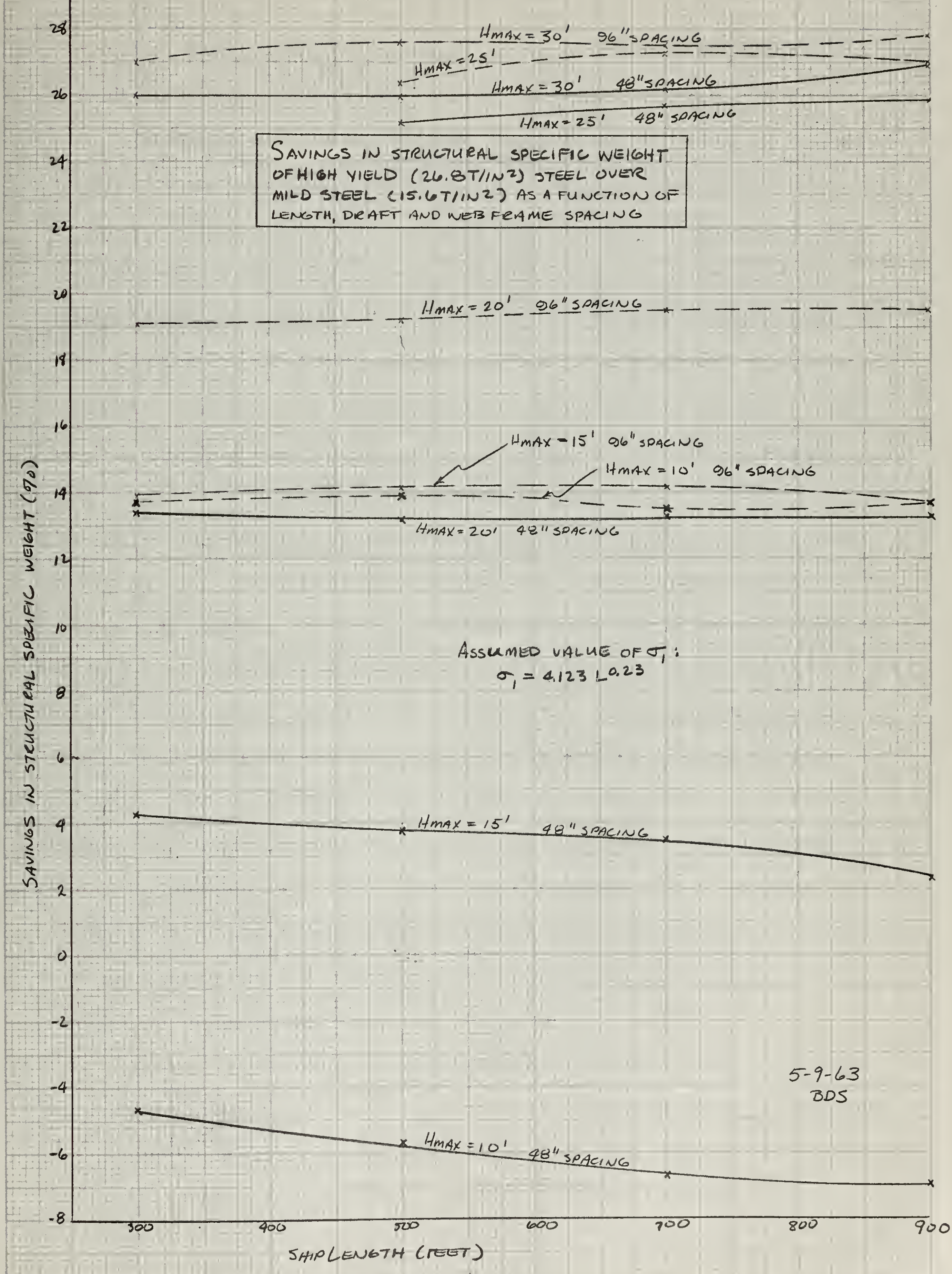

SAVINGS IN STRUCTURAL SPECIFIC WEIGHT OF HIGH YIELD (26.8T/IN²) STEEL OVER MILD STEEL AS A FUNCTION OF LENGTH, HEAD AND WEB FRAME SPACING
Hmax = 30'
Hmax = 30' 48" SPACING
Hmax = 20' 96" SPACING
Hmax = 25' 96" SPACING
VALUES OF Hmax = 20', 25' (48" SPACING) AND Hmax = 15' (96" SPACING) LIE WITHIN 16.9% AND 17.35%
Hmax = 10' 96" SPACING
Hmax = 15' 48" SPACING
NOTE: SCALE VALUE FOR σ1: σ1 = 3.0 L^0.23
Hmax = 10' 48" SPACING
5-9-63
BDS
SAVINGS IN STRUCTURAL SPECIFIC WEIGHT (%)
28
26
24
22
20
18
16
14
12
10
8
6
4
2
0
-2
-4
-6
-8
300
400
500
600
700
800
900
SHIP LENGTH (FT)

FIGURE 20



SAVINGS IN STRUCTURAL SPECIFIC WEIGHT OF HIGH YIELD (26.8T/IN²) STEEL OVER MILD STEEL (15.6T/IN²) AS A FUNCTION OF LENGTH, DRAFT AND WEB FRAME SPACING
Hmax = 30' 96" SPACING
Hmax = 25'
Hmax = 30' 48" SPACING
Hmax = 25' 48" SPACING
Hmax = 20' 96" SPACING
Hmax = 15' 96" SPACING
Hmax = 10' 96" SPACING
Hmax = 20' 48" SPACING
ASSUMED VALUE OF σ1:
σ1 = 4.123 L^0.23
Hmax = 15' 48" SPACING
Hmax = 10' 48" SPACING
5-9-63
BDS
SAVINGS IN STRUCTURAL SPECIFIC WEIGHT (%)
SHIP LENGTH (FEET)
28
26
24
22
20
18
16
14
12
10
8
6
4
2
0
-2
-4
-6
-8
300
400
500
600
700
800
900

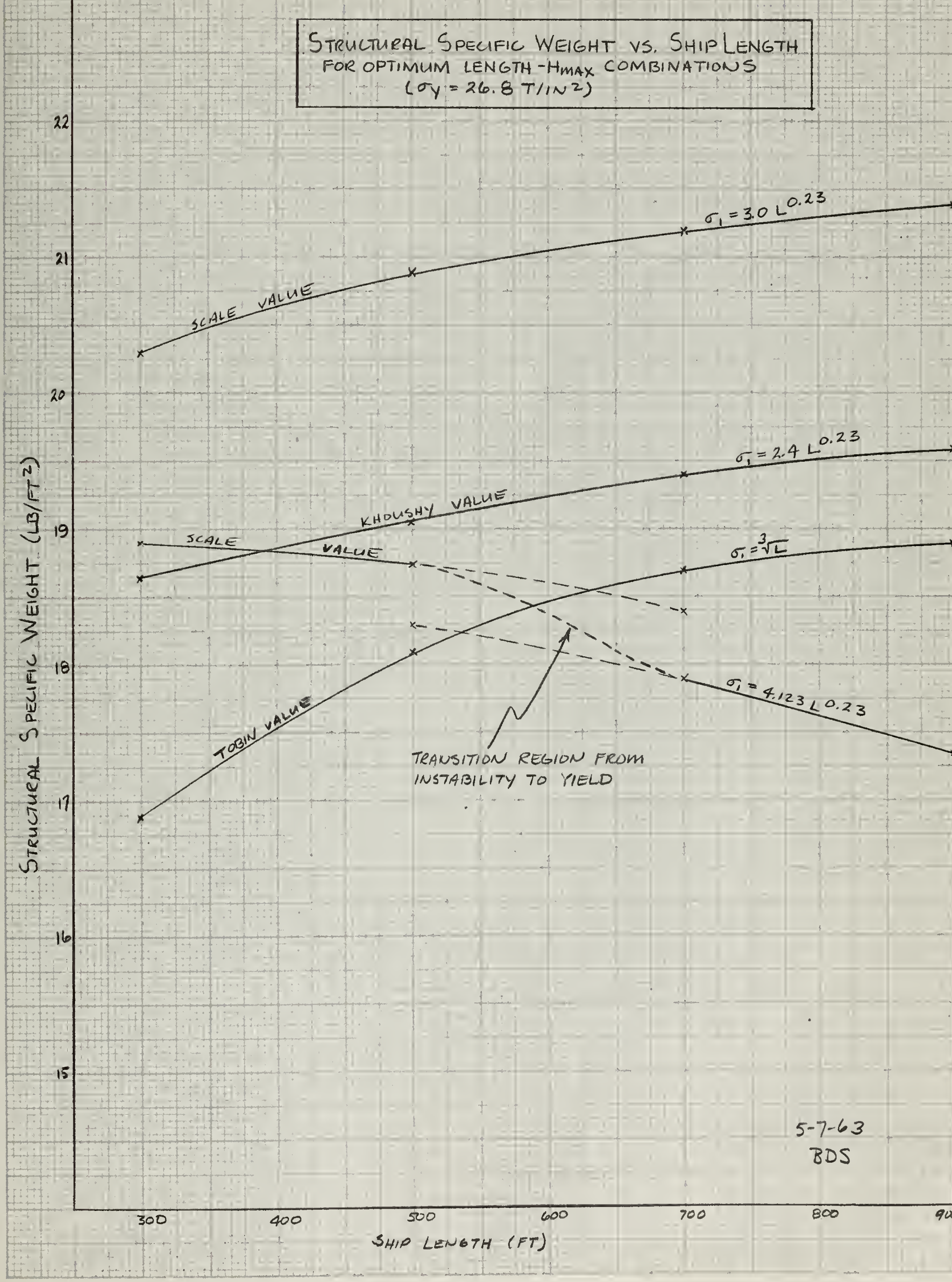
σ_{I}. (Fig. 21)

4. Average weight savings of high yield steel over mild steel as a function of H_{max} and ship length. (Fig. 22)

Certain conclusions can be drawn from the results listed above. From the first of the above, one can see that as values of H_{max} increase, for all the criteria considered, the difference becomes much less and may actually seem to converge around a certain value beyond which the value of head has little or no effect on the values of structural specific weight. Now one may incorporate the transverse weight of the web frame by comparing values of specific structural weight for the 48" and the 96" web frame spacings - the difference would be the weight of web frame per foot to make the values of γ equal. From past experience one could judge the size of web frame needed for a ship of the same dimensions and obtain a value of weight/transverse foot for it. If this weight is greater than the difference of weights, going to the shorter web frame spacing would be the equivalent of adding excess weight. If the weight of web frame were less, on the other hand, it would indicate that the smaller web frame spacing was preferable. If this model were extended to a greater number of assumed web frame spacings and the results compared, it is likely that a standard for choosing a web frame spacing could be determined.

Since the values of the difference become less and less for increasing values of H_{max} and since values of H_{max} generally increase with increasing ship length (and size), this indicates that the structural specific weight becomes increas-

Figure 21


STRUCTURAL SPECIFIC WEIGHT VS. SHIP LENGTH
FOR OPTIMUM LENGTH - Hmax COMBINATIONS
(σy = 26.8 T/IN²)
22
21
20
19
18
17
16
15
STRUCTURAL SPECIFIC WEIGHT (LB/FT²)
SCALE VALUE
σ₁ = 3.0 L^0.23
KHOUSHY VALUE
σ₁ = 2.4 L^0.23
SCALE VALUE
σ₁ = ∛L
TOBIN VALUE
σ₁ = 4.123 L^0.23
TRANSITION REGION FROM INSTABILITY TO YIELD
300
400
500
600
700
800
900
SHIP LENGTH (FT)
5-7-63
BDS

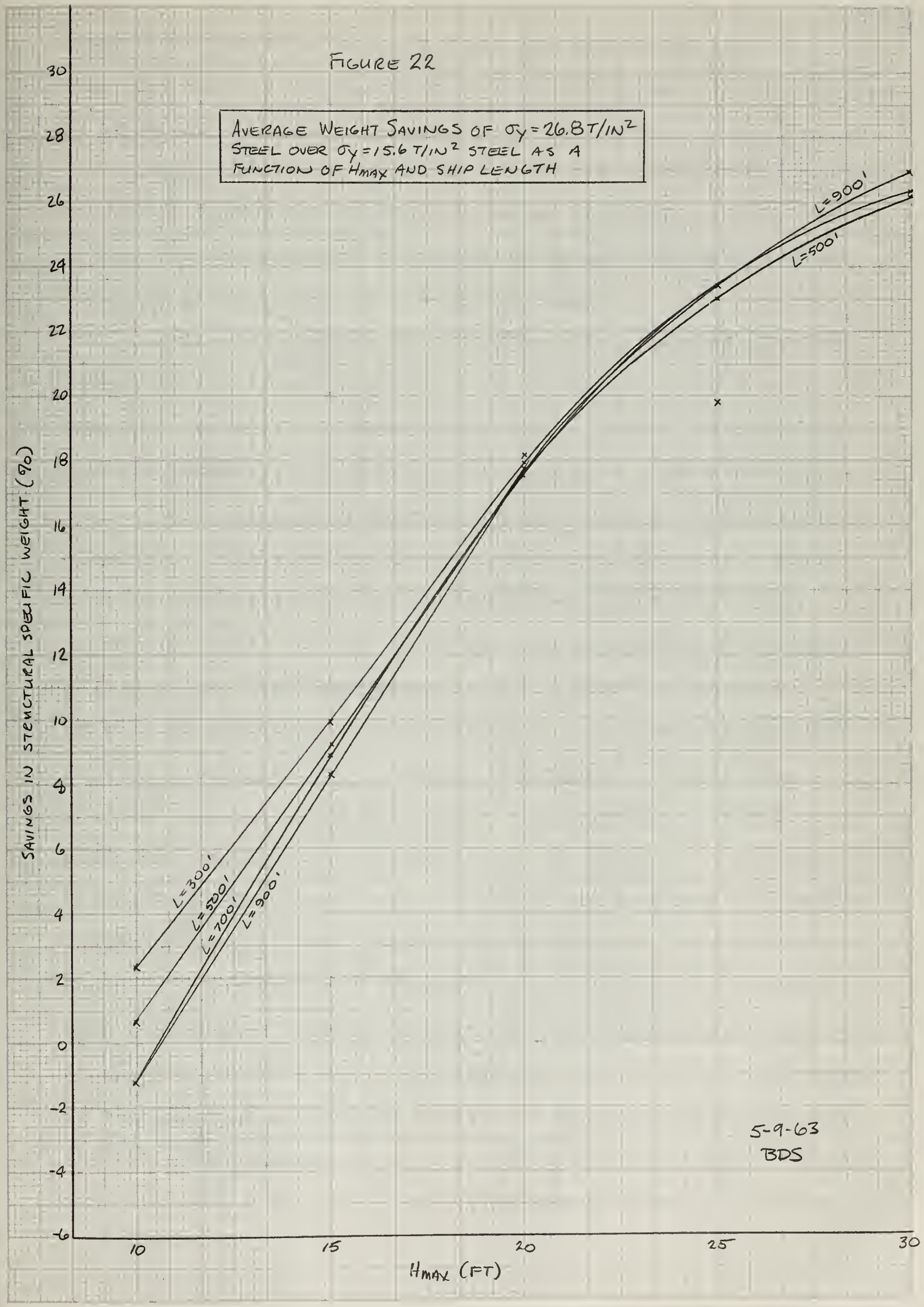


FIGURE 22
AVERAGE WEIGHT SAVINGS OF $\sigma_y = 26.8 T/IN^2$ STEEL OVER $\sigma_y = 15.6 T/IN^2$ STEEL AS A FUNCTION OF H_{max} AND SHIP LENGTH
SAVINGS IN STRUCTURAL SPECIFIC WEIGHT (%)
30
28
26
24
22
20
18
16
14
12
10
8
6
4
2
0
-2
-4
-6
10
15
20
25
30
H_{max} (FT)
L=300'
L=500'
L=700'
L=900'
L=900'
L=500'
5-9-63
BDS

ingly insensitive to the web frame spacing as the size of ship increases. The degree of insensitivity may be calculated, if necessary, should a designer wish to do so.

These curves also indicate the effect of the σ_1 criterion on the savings to be effected by using high yield steel, indicating the decreased difference with larger and larger values of σ_1 as given by the different σ_1 criteria.

Considering the second set of functions, the results are expressed in a percentage basis in order to provide a rapid means of comparison between designs on a length, maximum head and web frame spacing basis. Figures 17-20 show the convergence of the value of percentage weight savings of high yield steel over mild steel as the values of head increase. While this is another way of representing the previously-noted decreasing effect of web frame spacing on specific structural weight as the head increases, it also indicates that the effects of differences in the various σ_1 criteria become less important the greater the head. The negative values show that the designs using the larger σ_1 criteria are very inefficient because the bottom plating is required to be much heavier than that necessary to support the hydrostatic loading simply because it must support an excessive σ_1 load without buckling. For deep draft vessels this is of lesser concern than for shallow vessels because of the larger design head value of the former. One notes that the two values of σ_1 which result in the negative savings in structural specific weight are for the values of σ_1 greater than the Khoushy value (which corrects the Tobin value for a wastage allowance of 1/16"). To check

the validity of the higher σ_1 estimates for high yield steel, one would necessarily have to design a ship using high yield steel and then check to see if a larger σ_1 value than that given by Tobin was actually attainable or whether the increased longitudinal support requirements to resist the expected ship girder bending stress as a critical stress did not actually keep the actual section modulus of the midship section at such a level that the expected σ_1 value would not be developed.

From figure 21 we see the increasing values of structural specific weight with increasing values of σ_1 except for the highest value of σ_1. This anomaly occurs because the head values for which the transition from instability to yield design occurs are below those for the other three criteria and hence the bottom plating is thinner, yielding a lower structural specific weight value. Three things should be noted at this point, however, lest it appear that the high σ_1 value is substantiated:

1. For <u>comparable</u> length-head combinations the structural specific weight increases as the assumed maximum allowable σ_1 value increases and the plating thickness for the $\sigma_1 = 4.123L^{0.23}$ criterion is in every case the thickest.

2. The values of structural specific weights as shown in figure 21 cannot be compared directly to each other for they are for different configurations, i.e., maximum design head values. Each curve would be of interest only if a designer were using <u>one</u> σ_1 criterion to design and then comparing his results against the optimum curve for his

assumed σ_l value to see how well he has fared.

3. In view of the increasing plating thickness values with increasing assumed σ_l values the midship section modulus must also be increasing because both the plating and the longitudinals required to support the plating are becoming heavier. It thus becomes increasingly doubtful that the actual σ_l value obtained at the end of the first cycle would compare with the initial assumed σ_l value. It seems almost certain that it must be less, thus invalidating the original σ_l assumption.

With this in mind one would choose to develop a curve of optimum structural specific weights as a function of length for a proven and verified σ_l value and then use this curve as a design comparison value for subsequent designs.

The interruption in the $\sigma_l = 4.123L^{0.23}$ curve is due to a change in stiffener size to accommodate the plating, and this step-differential in stiffener sizes causes a discontinuity in the specific structural weight vs. ship length curve.

The curves for the 96" web frame spacing exhibit the same characteristics and will not be included in order to avoid redundancy.

Figure 22 shows the average weight savings of high yield steel over mild steel (as functions of head and ship length) for the four σ_l criteria mentioned previously. This indicates that the increasing weight savings with head has very little dependence on ship length. This indicates the fact that at the lower values of draft the high yield steel is not an efficient structural material because the thin plating is inadequate for the σ_l buckling stress and the resultant closer longitudinal spacing to bring the critical stress up to

the σ_1 stress expected adds appreciably to the value of specific structural weight. At higher values of head the rate of change of weight savings begins to decrease, reflecting the fact that the thickness of bottom plating as sized by the hydrostatic loading is beginning to show a buckling stress comparable to the expected σ_1 stress. When the plating thickness reaches such a size as to be able to carry the σ_1 stress without buckling and the designs of both structures are carried out on a yield basis, one would expect the average percentage weight savings to approach some asymptotic value proportional to the percentage difference in yield stresses modified by the non-linear effects of the longitudinal weight (due to the step change in longitudinal size with changes in plating size). The inefficiency of the use of high yield steel for the smaller values of head is shown by the small savings at low values. The larger savings for the shorter lengths in this region indicate the deleterious effect of the need to design for stability as the required buckling strength increases as the expected buckling stress increases with length.

For values of head on the order of 20'-25' there are three effects of interest that appear from the curves - the fact that they converge the closest, the fact that the rate of change of weight savings begins to decrease and the fact that there appears to be a crossover from the greatest weight savings being associated with the shortest length to the greatest weight savings being associated with the longest length.

The convergence of values around the 20'-25' region in-

dicates that there is a more or less common percentage weight savings in the region approaching the transition from instability to yield design. At the 25' level there is one data point which lies outside the curves for the 300' case which indicates the transition from instability to yield design - the heavier weight required for the instability design was causing it to become much less efficient than its neighbors until it made the transition at which point it again became comparable. The same would be true for the 500', 700' and 900' cases in all probability and would be shown if a closer incremental spacing of values of head had been calculated.

The crossover region in which the 900' ship shows a greater percentage savings than the 300' ship is probably due to the fact that there is a better balance between yield and instability weights here, i.e., the σ_1 and σ_{cr} values are closer. For the 300' ship the plating thickness to resist the hydrostatic loading is much greater than that required to resist the buckling influence of the σ_1 stress which is also the case for the less efficient mild steel design. Thus the 900' ship design more nearly approaches the optimum $\sigma_{cr} = \sigma_1$ value.

The decrease in the rate of change of weight savings reflects the transition to a yield design and ultimately it should become asymptotic to some fraction of the ratio of yield strengths. The almost constant rate of change in the region of low values of head reflects the decrease in requirements for heavy, closely-spaced longitudinals to provide stability where all systems are constrained to show L/r

values ≤ 35, the common slenderness ratio providing the means of correlating all designs into what approximates a linear relationship.

Thus we have uncovered some indications of the limitations of using high-yield steel as well as an idea of some of the advantages in weight savings which might accrue from its use. The primary thing which curtails the further use of high yield steel is that the lighter structural scantlings which result from a high yield steel design aggravate the problem of instability. However, while high yield steel is currently being used to reduce structural weight in submarine design to extend the maximum operational depth further, the trend toward ships of deeper draft (which would increase the bottom plating thickness requirements and thus encourage a high yield steel design) is restricted to a maximum permissible draft as determined by harbor facilities and navigational restrictions. A more precise knowledge of the boundary conditions and interaction effects of the ship's structure and of a maximum bending moment to be encountered might relax design criteria to the extent that the use of high-yield steel would be encouraged, but at this state of the art its applications are somewhat limited for the surface ship case.

CHAPTER IV

ADDITIONAL CONSIDERATIONS

There are several interesting effects which arise as a result of the preceding investigations and which warrant further discussion. In this chapter a mention will be made of them as an indication of a few of the areas of investigation which are available for future work.

One of the early assumptions made in establishing an analytic expression leading to the solution of longitudinal spacing for mild and high yield steel designs for the one sagging case was that the σ_2 stress was both small and constant. Having solved for the panel sizes, we may now look back and see how valid the assumption was.

For the case for which the model was developed, the σ_2 stress was developed as a result of the bottom plating bending as it spanned the web frame, being subject to hydrostatic loading on either side of the web frame. We can determine the σ_2 stress in the outer fiber of the shell plating at the point where the longitudinal crosses the web frame by treating the longitudinal and associated effective breadth of plating as a beam subject to a uniformly distributed load with the appropriate boundary conditions. The σ_2 stress at the mid-span of the web frame between longitudinals will probably be somewhat higher due to the fact that it does not have the longitudinal for support, but the σ_2 value at the longitudinal web frame juncture will probably be a good first-order approximation.

Considering the longitudinal and its effective breadth

of plating to be a beam with a uniformly distributed loading and with built-in ends, the loading can be expressed as

$$\frac{(60t)}{12} \cdot 64 \cdot H = 320tH \text{ lb/ft}$$

From the expression for a beam with built-in ends of length "ℓ" under a uniformly distributed load of "w" lb/ft the maximum bending moment is the moment at the supports which is

$$M_{max} = \frac{wL^2}{12}$$

which for our case where w = 320tH lb/ft and ℓ = a becomes

$$M_{max} = \frac{320tHa^2}{12} = 26.\dot{6}\ tHa^2(\text{ft-lb}) = 320tHa^2\ (\text{in-lb})$$

Since $\sigma = M/Z$ we can say

$$\sigma_2 = \frac{M_{max}}{Z_{beam}} = \frac{320tHa^2}{Z_{beam}} \left(\frac{lb}{in^2}\right) = \frac{tHa^2}{7Z_{beam}} \left(\frac{T}{in^2}\right) \qquad (37)$$

where $Z_{beam} \equiv$ section modulus of longitudinal and effective plating (in^3).

From this expression we can infer that σ_2 values will be influenced directly by the value of head and web frame spacing chosen. The length of ship will have little or no effect unless the requirements to meet the instability criterion of $\sigma_1 \leqq \sigma_{cr}$ result in a longitudinal spacing which is actually less than the effective breadth of plating, thus reducing the longitudinal-plating section modulus and increasing the σ_2 value. The yield strength of the material will also influence the longitudinal spacing and the thickness of plating which in turn will effect the σ_2 values. Because of the fact that longitudinal sizes are not continuous and one is forced to accept slenderness ratios that necessarily show similar "jumps" when one changes from one

longitudinal size to another (with the attendant large swings in values of Z_{beam}) it is not easy to draw rigorous conclusions concerning the effect of yield strength on σ_2. The best approach would seem to be to allow for larger assumed values of σ_2 with increasing head and web frame spacings and then check the assumed value once scantlings have been chosen. For an actual design where the web frame spacing has presumably been chosen already and for which the value of head for both the hogging and sagging cases will be fixed by the designed ship draft and assumed wave length, the assumption of a constant value for σ_2 is entirely proper. It would be interesting to determine the effect of the material on the σ_2 value, however, to determine whether the interaction effects of lighter plating weight and different longitudinal sizes to meet the limiting slenderness ratio would affect the assumed σ_2 value so as to enhance or detract from the use of a higher yield material.

The thicker the bottom plating becomes the heavier the stiffeners must be to succeed in defining the panel boundaries and in providing sufficient resistance against buckling. The effects of increasing the yield strength of the material and increasing the length of ship result in a closer longitudinal spacing and hence a larger percentage of the structural specific weight being taken up in weight of longitudinals. As mentioned earlier, Gerard [17] estimates that an optimum disposition of material would have 47% of the weight of structure in the longitudinals. For this case a reduction in the stiffener weight would be a major step toward reducing

the structural specific weight and the overall weight as well.

Because of its low weight and high modulus of elasticity beryllium is an interesting metal to consider. Also, because of its light weight, availability and ease of fabrication, aluminum is another interesting metal to consider.

Figure 23 shows a comparison of the structural specific weights for a bottom structure using steel, aluminum and beryllium stiffeners. The values for the aluminum and beryllium stiffeners were obtained by altering the density of the steel stiffener to correspond to the alternate material and then recomputing the value of structural specific weight. This is not a valid approach since the question of the stress distribution pattern and the effective value of the moment of inertia enter in for a composite structure, but for a first look at the situation this approach indicates the quality if not the quantity of the change.

When using different materials as in the case of a composite section one has to consider the effect of the modulus of elasticity of the material. The requirement to be met is that the strains be compatible at the juncture for the structure to be continuous. Since $\sigma = E\epsilon$ for the uniaxial stress case for a structure obeying Hooke's law, for strain compatability (continuous structure):

$$\epsilon_1 = \epsilon_2 \quad \text{whence} \quad \frac{\sigma_1}{E_2} = \frac{\sigma_2}{E_1} \quad \text{or} \quad \sigma_2 = \left(\frac{E_2}{E_1}\right)\sigma_1$$

In the case of aluminum the lower modulus of elasticity of aluminum means that it will deform more readily than steel and "shirk its duty," transferring the major share of the load

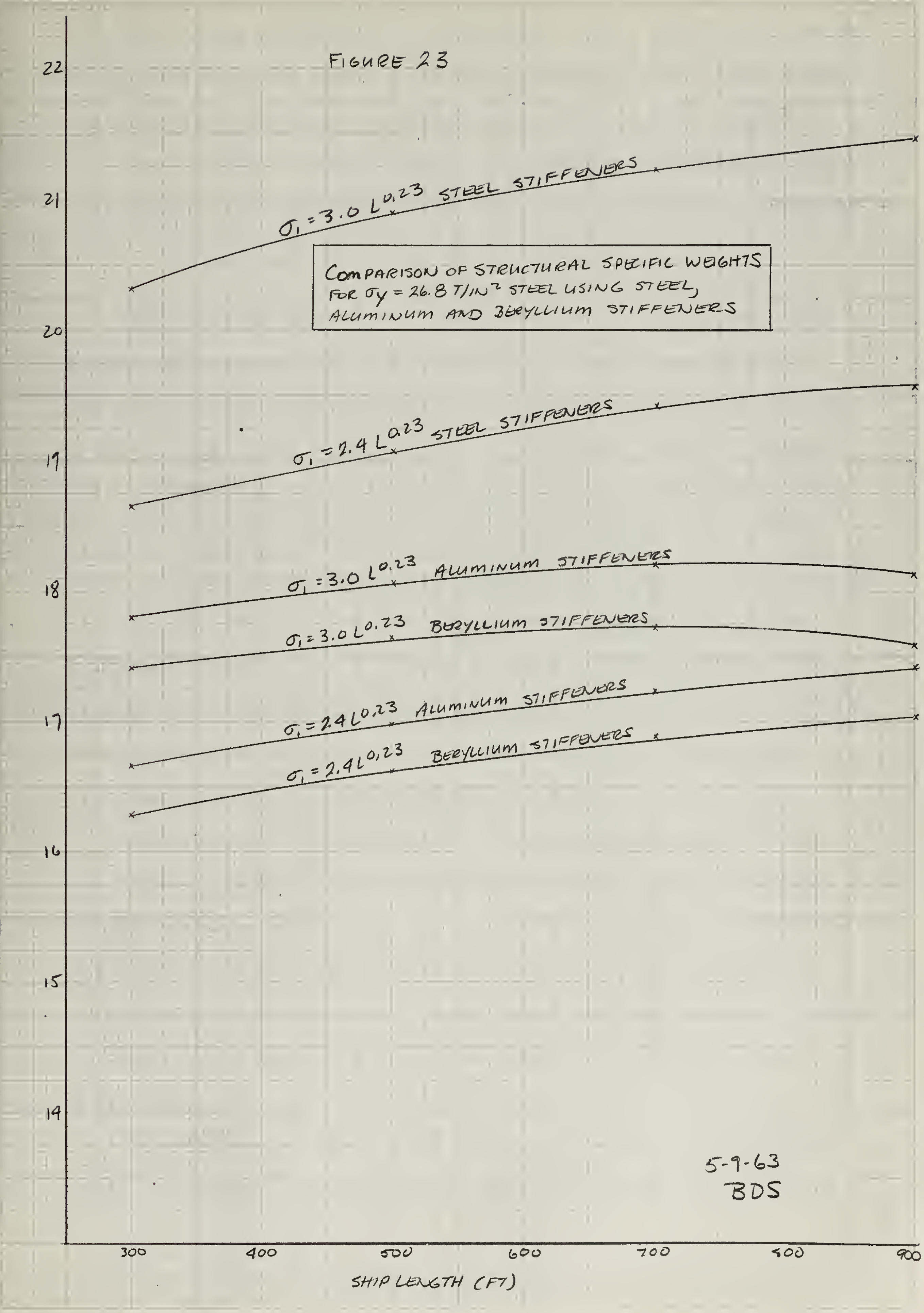


FIGURE 23
COMPARISON OF STRUCTURAL SPECIFIC WEIGHTS FOR $\sigma_y = 26.8\ T/IN^2$ STEEL USING STEEL, ALUMINUM AND BERYLLIUM STIFFENERS
$\sigma_1 = 3.0\ L^{0.23}$ STEEL STIFFENERS
$\sigma_1 = 2.4\ L^{0.23}$ STEEL STIFFENERS
$\sigma_1 = 3.0\ L^{0.23}$ ALUMINUM STIFFENERS
$\sigma_1 = 3.0\ L^{0.23}$ BERYLLIUM STIFFENERS
$\sigma_1 = 2.4\ L^{0.23}$ ALUMINUM STIFFENERS
$\sigma_1 = 2.4\ L^{0.23}$ BERYLLIUM STIFFENERS
22
21
20
19
18
17
16
15
14
300
400
500
600
700
800
900
SHIP LENGTH (FT)
5-9-63
BDS

into the steel structure. Beryllium, on the other hand, withstands deformation under load to a greater extent than steel and therefore carries the major share of the load itself.

One may now consider what this means in reference to the midship section. The ship girder stress is actually given by

$$\sigma_1 = \left(\frac{M}{Z}\right)$$

Recognizing that Z = I/C one can see the problem. The moment of inertia, I, is a function of the distribution of the area of the longitudinally continuous material about the neutral axis. The value of c, the distance from the neutral axis to the outermost fiber of the section in question, also depends upon the location of the neutral axis. Due to the fact that the section is not homogeneous, however, the neutral axis of the section "shifts" from where it would be for a homogeneous structure in order to maintain equilibrium and structural continuity. Thus the section modulus and also the resulting value of σ_1 will be different for a composite structure than for a homogeneous structure.

If one uses the procedure of choosing one material as the primary material and referring to the areas of sections of different materials by the ratio of the moduli of elasticity one can obtain an effective moment of inertia and an effective section modulus. With these one can proceed further to develop a stress distribution pattern for the midship section.

If we now consider the aluminum or beryllium stiffener case, it becomes apparent that each would best be used in a

different location. The aluminum would best be used in way of the neutral axis of the midship section for three reasons. The first is that the moment of inertia/section modulus combination is relatively insensitive to the material in this section due to its small lever arm. The second is that the σ_1 stresses are low here and the effect of the lower modulus of elasticity value of aluminum on structural instability would not be felt to the extent that they would, say, in the deck or bottom. The point at which σ_1 begins to become critical could be determined and the use of aluminum stiffeners curtailed beyond that point. The third reason is that the shell plating is thinnest in way of the neutral axis, and thus the stiffener would contribute most effectively to its support in that location.

Beryllium stiffeners, on the other hand, would be most effective in the deck or bottom for reasons corresponding to its higher modulus of elasticity. The use of beryllium stiffeners in the deck alone might effectively raise the neutral axis to the mid-depth and thus develop the full strength of the section. Furthermore, the beryllium stiffeners could bear a greater share of the σ_1 stress and thus allow a thinner shell plating without fear of buckling due to plate instability, allowing high yield steel to develop more of its potential for weight savings based primarily on the hydrostatic loading basis.

While the use of aluminum, beryllium or other stiffeners is not immediately at hand at this time, it is possible that they may be considered at some future date. The possibility

of weight savings through their use is such that a further consideration of the foregoing, perhaps particularly in the case of aluminum, could be of more than academic interest.

Next we may consider constructing a ship of aluminum. The advantages here are several - lighter weight, greater payload, reduced draft for a given payload and so forth. The economics of the situation, particularly the welding costs, are not encouraging but the case is interesting.

Structural weight depends on the scantlings of the structure which in turn depend on the material used and the conditions to be met. Considering figure 6, a handout for the course in preliminary design of ships at M.I.T., one can see that structural weight is a considerable portion of a ship's designed displacement, and a reduction in the structural weight would clearly be an advantage. The curve of hull, hull fittings and equipment runs from 20% to about 37.5% of the designed displacement. If we assume that hull fittings and equipment run about 30% of the total, this would mean that the hull weight would run from 14% to 26.2% of the designed displacement. Hull fittings and equipment being a value which is probably relatively fixed (such as anchor handling gear, boat handling gear, etc.), the larger the ship the larger the percentage hull weight and the smaller the equipment and fitting weight in proportion would seem to be the case.

There are many different ways to arrive at the calculation of the maximum bending moment amidships. A common factor to most of them is the calculation of the weight distribution curve, a nice description of which may be found in [24]. Now

$$M_{\otimes} = \iint_L (b-w)dxdx$$

where $\quad b \equiv$ buoyancy per foot of length

$\quad\quad\quad w \equiv$ weight per foot of length

and to be entirely correct one would integrate graphically along the length. The Navy procedure, however, is to break the ship into twenty stations, find the average buoyancy/ft and the average weight/ft across the section, obtain the difference of the two average values and proceed from there. The effect of averaging the weight and buoyancy values over incremental lengths has been perfectly acceptable for years for the Navy so we shall adopt its use here also.

We can express the ship's design displacement as

$$\Delta = W_H + W_M + W_F + W_p + W_x$$

where

$\Delta \equiv$ design displacement $\quad\quad W_H \equiv$ weight of hull structure

$W_M \equiv$ weight of machinery $\quad\quad W_F \equiv$ weight of fuel

$W_p \equiv$ weight of payload $\quad\quad W_x \equiv$ remaining weight

Since $(b-w) = \dfrac{d\Delta}{dx} = \dfrac{\partial W_H}{\partial x} + \dfrac{\partial W_M}{\partial x} + \dfrac{\partial W_F}{\partial x} + \dfrac{\partial W_p}{\partial x} + \dfrac{\partial W_x}{\partial x}$

$$M_{\otimes} = \iint_L \left(\frac{\partial W_H}{\partial x} \quad \frac{\partial W_M}{\partial x} \quad \frac{\partial W_F}{\partial x} \quad \frac{\partial W_p}{\partial x} \quad \frac{\partial W_x}{\partial x} \right) dxdx$$

For a ship whose structural scantlings can be chosen on a yield design basis ($\sigma_1 < \sigma_{cr}$) the use of aluminum for the hull structure will allow reductions in W_H and $W_F + W_M$ as well (since propulsion requirements are a function of displacement and fuel requirements depend on propulsion require-

ments). This overall reduction in the value of $M_{\emptyset}$ will allow further reductions in midship section scantling requirements which will lead to reduced hull weight and further reductions in powering requirements. Since $\rho_{aluminum} = 0.3427\ \rho_{steel}$ the hull weight itself should be reduced on this order. Considering the hull structural weight to be on the order of 70% of the hull, hull fittings and equipment weight curve of figure 6, this would mean a savings in displacement of from 4.8% to 9% depending on the speed-length ratio not considering the reductions on the machinery weight and fuel groups which would result from the decreased displacement.

The effect of building the hull from aluminum, then, would provide a savings in weight which could be used:

1. To reduce construction costs due to the lighter hull and reduced powering requirements (main propulsion machinery)

2. To provide for an increased payload to bring the aluminum displacement up to the equivalent steel displacement level.

The design must be restricted to a ship of limited length, however, because the lower value of modulus of elasticity for aluminum lowers the critical stress for aluminum to a value just slightly greater than one-third that of steel. The design of aluminum for the case of instability would be possible, but the additional weight required would limit the savings that would otherwise be realized. In addition to this, welding costs and difficulties for large sections of aluminum would cause a large increase in cost for the aluminum design

faced with instability. The economic feasibility of the design would depend on the results of the service life with added payload return for high initial cost and maintenance expense.

A measure of comparison for different ship designs has been proposed by Gerard and Lewis in [17]. We have already considered the solidity concept and substituted for it the structural specific weight concept. Now let us examine the structural loading index concept.

Shanley [28] advances the idea of comparing designs using a pseudo-stress which is the quotient of a structural loading divided by representative structural parameters. For the case of a ship the structural loading index advanced was M_x/BD^2. The structural loading index is a measure of the intensity of the loading of the structure, has the units of a stress and has the value of eliminating the effects of size and being a comparison of the efficiency of the material when plotted against the design stress of the structure. A comparison of structures on the basis of structural loading index plotted against allowable stress allows:

1. Comparison of various designs for a given material
2. Comparison of different materials.

The larger the value of stress developed for a given structural loading index, the more efficient the design (or the lower the factor of safety). These values of σ_1 for the ship case would necessarily be the actual σ_1 values obtained from the final design because the estimated σ_1 values are "target" values and subject to correction. Also, for the

ship design case there is no "nice" basis of comparison because of the <u>combined</u> effects of the three stresses - σ_1, σ_2 and σ_3. On this basis the ordinate of specific structural weight would be more indicative of an optimum design than any of the three single stresses (each based on a different criterion). On the basis of structural loading index vs. structural specific weight, then, one <u>could</u> develop curves for an optimum structural specific weight and then use these as reference values for comparison with subsequent designs.

The structural loading index advanced by Gerard and Lewis could stand a modification which would give it a more meaningful appearance for the case of comparison against a weight index. The previous value of BD^2 is comparable to a gross section modulus of a ship whence $M_{\emptyset}/BD^2$ gives a pseudo stress as a result. For our purposes let us take Lewis' expression for $M_{\emptyset}$

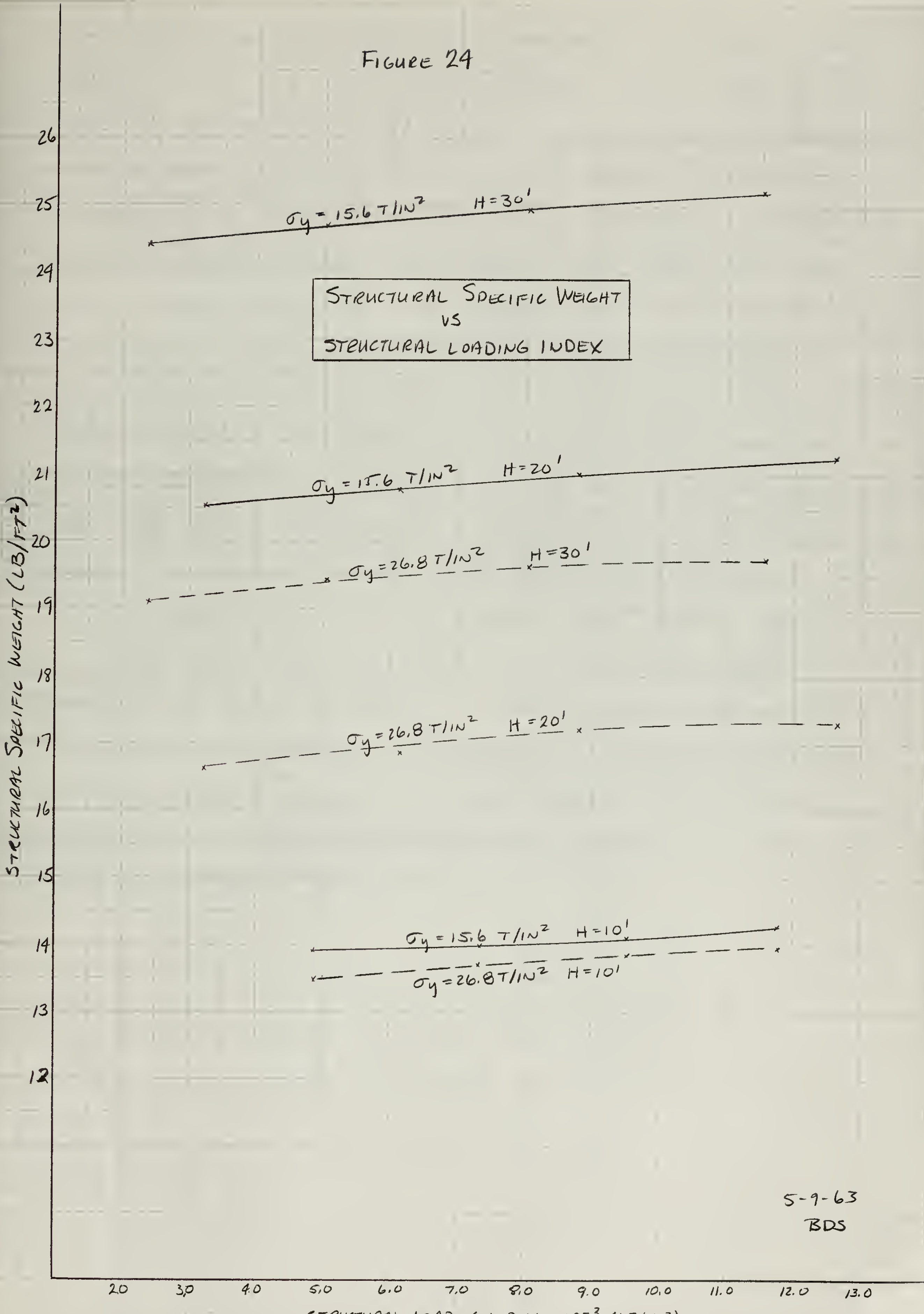
$$M_{\emptyset} \propto \rho g L^2 BHC_b$$

For a given ship we can assume ρ, g and C_b are constants which can be absorbed within the proportional sign. Thus

$$\frac{M_{\emptyset}}{BD^2} \propto \frac{L^2BH}{BD^2} \propto \frac{H}{(D/L)^2}$$

Given values of length and draft, one can enter the Load Line Regulations [30] and obtain values of freeboard and thus determine values of D. Now if one plots structural specific weight vs. structural loading index (modified), one can obtain the results mentioned earlier by Shanley, i.e., comparison of different designs on a weight basis and comparison of different designs. Figure 24 shows the results

FIGURE 24



STRUCTURAL SPECIFIC WEIGHT
VS
STRUCTURAL LOADING INDEX
σy = 15.6 T/IN² H = 30'
σy = 15.6 T/IN² H = 20'
σy = 26.8 T/IN² H = 30'
σy = 26.8 T/IN² H = 20'
σy = 15.6 T/IN² H = 10'
σy = 26.8 T/IN² H = 10'
26
25
24
23
22
21
20
19
18
17
16
15
14
13
12
STRUCTURAL SPECIFIC WEIGHT (LB/FT²)
2.0
3.0
4.0
5.0
6.0
7.0
8.0
9.0
10.0
11.0
12.0
13.0
STRUCTURAL LOADING INDEX x10⁻³ (LB/FT²)
5-9-63
BDS

for a mild steel-high yield steel comparison for a web frame spacing of 48" and the Khoushy criterion for σ_1. One can see that the structural specific weight increases as the structural loading index (intensity of loading) increases, that it increases as the value of head increases, that the structural specific weight of high yield steel is less than mild steel for all common values of head and that the rate of change of increase of structural specific weight for mild steel with increasing draft is much more than for high yield steel. These effects indicate the higher loading intensity per pound of structural weight that can be borne by the high yield steel, i.e., the higher "structural efficiency" of the high yield steel. The results for the larger web frame spacing and for different criteria for σ_1 have the same general shape.

This chapter has indicated a few of the sidelights of refining the model, putting it to use and using the results for comparative purposes. The avenues of interest available are many, and it is hoped that this chapter, in particular, has served to stimulate further investigations as to the uses and effects of new materials.

CHAPTER V

CONCLUSIONS

From the investigation thus completed, the following conclusions are drawn:

1. The variations in ρ, E and μ for a given material can cause a variation in critical stress of as high as 5.75% with a resultant weight variation on the order of 2.4%.

2. The use of a critical strength/weight ratio of $E/\rho(1-\mu^2)$ and a yield strength/weight ratio of σ_y/ρ allows a rational comparison of the advantages of different materials for the two different design criteria.

3. Of those metals considered aluminum showed the greatest merit for the yield design criterion, beryllium for instability.

4. Changes in material properties are less likely to be of future benefit in weight reduction than advances in defining structural loadings and boundary conditions.

5. The effect of reduced section modulus scantlings on flexure may prove to be of some concern, especially since dynamic loadings on the order of 100% of the design values have already been measured in models.

6. The effect of decreased displacement due to smaller hull weight would serve to decrease the natural period of the ship, increase the natural frequency and decrease the chance that the ship would approach motion and possibly flexual resonance in a seaway.

7. A σ_1 value larger than the Khoushy or Tobin values

should be developed for high-yield steel to reflect the probable increase in available yield stress. The increase, however, will probably be small and possibly less than the ratio of the ultimate strengths of the materials.

8. Minimizing σ_1 for a metal also maximizes σ_3 which results in thinner bottom plating and less weight. An optimum σ_1 value for high yield steel should be sought.

9. Using the procedure outlined in Chapter II and having a good expression for σ_1 one could determine for what values of length and maximum head an optimum design would result as shown by the transition curve between the yield and instability domains.

10. To enhance the possibility of a yield design (which would be lighter than an instability design) one would seek to build deeper ships or ships of greater draft.

11. Values of specific structural weight become increasingly insensitive to web frame spacing as values of design head increase.

12. Having values of specific structural weight for two web frame spacing values and estimating the weight of web frame/transverse foot, one can choose between web frame spacings on a least-weight basis.

13. The more optimum the design the greater the weight savings that can be achieved by using aluminum or beryllium stringers.

14. A composite midship section of high yield steel shell plating, beryllium bottom and deck stringers and aluminum side stringers would provide strength with low weight.

15. The savings in weight between high yield steel and mild steel construction have a relatively small dependence on length, are dependent largely on head and seem to reach a common upper value above a limiting value of head.

16. The value of σ_2 can be assumed constant for a given ship design case but will vary between designs with different values of web frame spacing, draft, etc., and should be calculated separately for each different design condition.

17. The use of stiffeners of different materials may allow control of the midship section neutral axis in such manner as to locate it at mid-depth and develop the full strength of the section.

18. The idea of an all-aluminum ship is interesting, but it would probably be limited by the expected σ_1 stresses to a relatively short length.

19. The modified structural loading index would be a good way to compare designs on the basis of design efficiency and type of material. The structural loading index incorporates the effect of the important parameters length, depth and draft.

20. On a basis of weight, high-yield steel is more structurally efficient than mild steel as shown by its lower structural specific weight for a given value of structural loading index.

21. The effects of high-yield steel are more apparent and of more significance the heavier the structure.

In conclusion it should be noted that while the simplifying assumptions as to the magnitude of σ_2 stresses and

longitudinal sizes for the yield case put the results on a qualitative more than a quantitative basis the model provides a good qualitative idea of the effects to be expected. Further refinement of the model would yield more quantitative data.

CHAPTER VI

RECOMMENDATIONS

As a result of this investigation and the conclusions which have been presented, the following recommendations are made as suggested areas of further investigation:

1. Using Bleich's works on buckling of metal structures [3] and [4] develop a good method of estimating the degree of edge restraint for various plating-stiffener combinations.

2. Investigate the slenderness ratio concept to obtain a sound criterion for limiting values for plating-stiffener combinations.

3. Investigate the effects of the various different formulas for effective width and effective breadth of plating on the design.

4. Investigate the effects of reduced midship moment of inertia values on dynamic bending moment.

5. Develop a rational σ_1 value for high yield steels.

6. Refine the model developed in the thesis to incorporate a varying value of σ_2 and consider the case of the inner plating, hogging condition for comparative purposes.

7. Conduct a feasibility study of a midship section design using aluminum stringers in way of the neutral axis.

8. Incorporate transverse (web frame) weight into the structural specific weight model.

9. Calculate transition curves from yield to instability for aluminum designs; determine feasible ship length for an all-aluminum ship.

10. Conduct a feasibility study on the use of new materials on an economic basis.

11. Develop and compare results of models for the different design cases (hogging, sagging, etc.)(with proper σ_2 values and appropriate factor of safety) to determine an initial estimate for longitudinal spacings.

12. Determine the effect of high yield steel on σ_2 estimates.

13. Investigate the critical stress value for panel instability, extend this from elastic to plastic buckling and revise the model accordingly.

14. Determine the effects of increased hull flexure on structural adequacy in a seaway.

15. Determine the effects of longitudinal framing on stress distribution across a ship's bottom (see Vasta [31]) and investigate for the expected stress the bottom must stand without buckling.

CHAPTER VII

APPENDIX

APPENDIX A

RESULTS OF CALCULATIONS

VALUES OF L' FROM SOLUTION FOR SCANTLINGS
BASED ON TOBIN VALUE FOR

$$\sigma_1 = \sqrt[3]{L}$$

H	L	a	b	t	a/b	t/b	k_c	σ_{cr} clamped	L'
10	300	48	39.7	0.233	1.21	1/170	7	6,700	26.7
		96	79.4	0.466					
	500	48	38.4	0.234	1.25	1/164	7	7,210	33.5
		96	76.8	0.468					
	700	48	37.5	0.2355	1.28	1/159	7	7,680	40.5
		96	75.0	0.471					
	900	48	36.6	0.2355	1.31	1/155	7	8,080	46.75
		96	73.2	0.471					
15	300	48	39.0	0.280	1.23	1/139	7	10,000	89
		96	78.0	0.560					
	500	48	37.6	0.281	1.28	1/134	7	10,800	112
		96	75.2	0.562					
	700	48	36.5	0.282	1.32	1/129.3	7	11,600	139
		96	73.0	0.564					
	900	48	35.7	0.283	1.35	1/126	7	12,220	161
		96	71.4	0.566					
20	300	48	38.9	0.323	1.24	1/120.5	7	13,370	210
		96	77.8	0.646					
	500	48	37.4	0.3255	1.28	1/115	7	14,700	281
		96	74.8	0.651					
	700	48	36.4	0.3255	1.32	1/112	7	15,450	330
		96	72.8	0.651					
	900	48	36.1	0.329	1.33	1/109.8	7	16,100	373
		96	72.2	0.658					
25	300	48	39.6	0.368	1.21	1/107.6	7	16,800	420
		96	79.2	0.736					
	500	48	38.4	0.370	1.25	1/103.8	7	18,000	520
		96	76.8	0.740					
	700	48	37.4	0.370	1.28	1/101	7	19,000	605
		96	74.8	0.740					
	900	48	36.55	0.372	1.31	1/98.3	7	20,100	720
		96	73.1	0.744					
30	300	48	38.7	0.394	1.24	1/98.25	7	20,150	740
		96	77.4	0.792					
	500	48	37.5	0.396	1.28	1/94.6	7	21,650	925
		96	75.0	0.792					
	700	48	36.5	0.397	1.32	1/92	7	22,950	1090
		96	73.0	0.794					
	900	48	35.7	0.399	1.35	1/89.5	7	24,200	1270
		96	71.4	0.798					

VALUES OF γ FOR TOBIN VALUE $\sigma_1 = \sqrt[3]{L}$

H	L	a	σ_{cr}	t	$b_{orig.}$	b_{new}	STIFFENER #/ft.	γ
10	300	48	15,000	0.233	39.7	26.5	7.0	12.74
		96	"	0.466	79.4	53.0	14.91	22.55
	500	48	17,750	0.234	38.9	24.5	7.0	13.02
		96	"	0.468	76.8	49.0	14.91	22.92
	700	48	19,900	0.2355	37.5	23.25	7.0	13.3
		96	"	0.471	75.0	46.5	14.91	23.23
	900	48	21,600	0.2355	36.6	22.35	7.0	13.42
		96	"	0.431	73.2	44.7	14.91	23.4
15	300	48	15,000	0.280	39.0	31.8	8.25	14.62
		96	"	0.560	78.0	63.6	20.06	26.8
	500	48	17,750	0.281	37.6	29.4	8.25	14.92
		96	"	0.562	75.2	58.8	20.06	27.2
	700	48	19,900	0.282	36.5	27.85	8.25	15.16
		96	"	0.564	73.0	55.7	20.06	27.5
	900	48	21,600	0.283	35.7	26.8	8.25	15.32
		96	"	0.566	71.4	53.6	20.06	27.8
20	300	48	15,000	0.323	38.9	36.75	8.25	16.0
		96	"	0.646	77.8	73.5	20.06	29.82
	500	48	17,750	0.3255	37.4	34.0	8.25	16.29
		96	"	0.651	74.8	68.0	20.06	30.3
	700	48	19,900	0.3255	36.4	32.05	8.25	16.49
		96	"	0.651	72.8	64.1	20.06	30.6
	900	48	21,600	0.329	36.1	31.2	8.25	16.70
		96	"	0.658	72.2	62.4	20.06	30.9
25	300	48	-	0.368	39.6	-	2.75	16.0
		96	-	0.736	79.2	-	12.01	32.1
	500	48	-	0.370	38.4	-	2.75	16.06
		96	-	0.740	76.8	-	12.01	32.25
	700	48	-	0.370	37.4	-	2.75	16.12
		96	-	0.740	74.8	-	12.01	32.4
	900	48	-	0.372	36.55	-	2.75	16.20
		96	-	0.744	73.1	-	12.01	32.55
30	300	48	-	0.394	38.7	-	3.25	17.15
		96	-	0.788	77.4	-	12.01	34.2
	500	48	-	0.396	37.5	-	3.25	17.30
		96	-	0.792	75.0	-	12.01	34.45
	700	48	-	0.397	36.5	-	3.25	17.40
		96	-	0.794	73.0	-	12.01	34.6
	900	48	-	0.399	35.7	-	3.25	17.48
		96	-	0.798	71.4	-	12.01	34.8

SUMMARY OF RESULTS USING KHOUSHY VALUE

$$\sigma_1 = 2.4L^{0.23}$$

H	L	σ_y	b	a	t	a/b	t/b	k	σ_{cr}	L'	τ	STIFFNER #/FT
10	300	15.6	28.95	48	0.317	1.655/1.6	1/91.4	7.2	23900	660	13.95	2.2
			57.9	96	0.634						27.75	8.25
		26.8	37.5	48	0.2355	1.28/1.3	1/159	7.0	7680	4.75	10.38	2.2
			75.0	96	0.471						20.1	4.5
	500	15.6	25.9	48	0.317	1.85/1.6	1/81.7	7.04	29200	71000'	14.04	2.2
			51.8	96	0.634						28.0	8.25
		26.8	36.15	48	0.2355	1.329/1.3	1/153.5	7.00	8250	6.45	10.41	2.2
			72.3	96	0.471						20.1	4.5
	700	15.6	23.55	48	0.317	2.04/1.6	1/74.3	7.00	35200	71000'	14.15	2.2
			47.1	96	0.634						28.15	8.25
		26.8	35.4	48	0.238	1.358/1.4	1/148.8	7.00	8750	8.4'	10.53	2.2
			70.8	96	0.476						20.4	4.5
	900	15.6	21.4	48	0.317	2.24/1.6	1/67.5	7.00	42600	71000'	14.3	2.2
			42.8	96	0.634						28.4	8.25
		26.8	34.7	48	0.238	1.385/1.4	1/146	7.00	9100	9.8	10.7	2.2
			69.4	96	0.476						20.3	4.5
15	300	15.6	28.6	48	0.384	1.68/1.6	1/74.5	7.15	35700	71000'	17.15	3.25
			57.2	96	0.768						34.0	12.01
		26.8	36.7	48	0.282	1.31/1.3	1/130	7.00	11500	26.5	12.33	2.2
			73.4	96	0.564						24.1	5.9
	500	15.6	25.6	48	0.384	1.873/1.6	1/65.7	7.02	45000	71000'	17.35	3.25
			51.2	96	0.768						34.45	12.01
		26.8	35.4	48	0.284	1.356/1.4	1/124.6	7.00	12500	40	12.4	2.2
			70.8	96	0.568						24.35	5.9
	700	15.6	23.25	48	0.384	2.06/1.6	1/60.5	7.00	53000	71000'	17.51	3.25
			46.5	96	0.768						34.7	12.01
		26.8	34.5	48	0.284	1.392/1.4	1/121.4	7.00	13170	48.75	12.45	2.2
			69.0	96	0.568						24.4	5.9
	900	15.6	21.2	48	0.384	2.26/1.6	1/55.25	7.00	63500	71000'	17.60	3.25
			42.4	96	0.768						34.95	12.01
		26.8	33.8	48	0.284	1.42/1.4	1/119	7.00	13700	58.5	12.45	2.2
			67.6	96	0.568						24.6	7.0
20	300	15.6	29.6	48	0.456	1.62/1.6	1/64.9	7.25	47900	71000'	20.55	4.5
			59.2	96	0.912						40.2	13.86
		26.8	36.75	48	0.3255	1.307/1.3	1/113	7.00	15200	91	14.09	2.2
			73.5	96	0.651						28.1	8.25
	500	15.6	26.5	48	0.456	1.81/1.6	1/58.0	7.05	58000	71000'	20.8	4.5
			53.0	96	0.912						40.6	13.86
		26.8	35.4	48	0.3255	1.357/1.3	1/108.9	7.00	16400	127.5	14.12	2.2
			70.8	96	0.651						28.15	8.25
	700	15.6	24.05	48	0.456	1.995/1.6	1/52.7	7.00	70000	71000'	21.0	4.5
			48.1	96	0.912						41.0	13.86
		26.8	34.8	48	0.330	1.38/1.4	1/105.3	7.00	17500	168'	14.30	2.2
			69.6	96	0.660						28.55	8.25
	900	15.6	21.85	48	0.456	2.2/1.6	1/47.9	7.00	84800	71000'	21.25	4.5
			43.7	96	0.912						41.4	13.86
		26.8	34.1	48	0.330	1.41/1.4	1/103	7.00	18200	200	14.33	2.2
			68.2	96	0.660						28.6	8.25

VALUES OF L' AND γ FOR KHOUSHY VALUE OF

$$\sigma_1 = 2.4L^{0.23}$$

H	L	σ_y	b	a	t	a/b	t/b	k	σ_{cr}	L'	γ	STIFFNER #/FT
25	300	15.6	29.15	48	0.504	1.648/1.6	1/58	7.20	59500	>1000'	22.75	5.15
			58.3	96	1.008						46.0	22.5
		26.8	37.5	48	0.372	1.28/1.3	1/101	7.00	19000	240'	16.31	3.25
			75.0	96	0.744						32.5	12.01
	500	15.6	26.05	48	0.504	1.84/1.6	1/51.9	7.03	72500	>1000'	23.07	5.15
			52.1	96	1.008						46.55	22.5
		26.8	36.1	48	0.372	1.33/1.3	1/97	7.00	20650	350'	16.36	3.25
			72.2	96	0.744						32.6	12.01
	700	15.6	23.65	48	0.504	2.04/1.6	1/47	7.00	87750	>1000'	23.35	5.15
			47.3	96	1.008						47.3	22.5
		26.8	35.4	48	0.376	1.356/1.4	1/94.1	7.00	21900	450'	16.51	3.25
			70.8	96	0.752						33.0	12.01
	900	15.6	21.6	48	0.504	2.22/1.6	1/42.9	7.00	105600	>1000'	23.6	5.15
			43.2	96	1.008						47.6	22.5
		26.8	34.6	48	0.376	1.39/1.4	1/92	7.00	22950	550	16.55	3.25
			69.2	96	0.752						33.0	12.01
30	300	15.6	28.6	48	0.542	1.68/1.6	1/52.75	7.15	71250	>1000'	24.45	5.15
			57.2	96	1.084						49.4	22.5
		26.8	36.55	48	0.3975	1.315/1.3	1/92	7.00	22900	540'	17.4	3.25
			73.1	96	0.795						34.7	12.01
	500	15.6	25.65	48	0.542	1.87/1.6	1/47.4	7.02	86800	>1000'	24.7	5.15
			51.3	96	1.084						50.0	22.5
		26.8	35.4	48	0.401	1.356/1.4	1/88.25	7.00	24950	790'	17.59	3.25
			70.8	96	0.802						34.95	12.01
	700	15.6	23.3	48	0.542	2.06/1.6	1/43	7.00	105000	>1000'	24.93	5.15
			46.6	96	1.084						50.4	22.5
		26.8	34.4	48	0.401	1.40/1.4	1/85.75	7.01	26,400	1000'	17.62	3.25
			68.8	96	0.802						35.1	12.01
	900	15.6	21.2	48	0.542	2.26/1.6	1/39.1	7.00	127000	>1000'	25.2	5.15
			42.4	96	1.084						50.95	22.5
		26.8	33.8	48	0.401	1.42/1.4	1/84.3	7.00	27300	>1000'	17.66	3.25
			67.6	96	0.802						35.15	12.01

VALUES OF L' AND γ FOR KHOUSHY VALUE OF

$$\sigma_1 = 2.4L^{0.23}$$

H	L	σ_y	b	a	t	a/b	t/b	k	σ_{cr}	L'	γ	STIFFENER #/FT
25	300	15.6	29.15	48	0.504	1.648/1.6	1/58	7.20	59500	>1000'	22.75	5.15
			58.3	96	1.008						46.0	22.5
		26.8	37.5	48	0.372	1.28/1.3	1/101	7.00	19000	240'	16.31	3.25
			75.0	96	0.744						32.5	12.01
	500	15.6	26.05	48	0.504	1.84/1.6	1/51.9	7.03	72500	>1000'	23.07	5.15
			52.1	96	1.008						46.55	22.5
		26.8	36.1	48	0.372	1.33/1.3	1/97	7.00	20650	350'	16.36	3.25
			72.2	96	0.744						32.6	12.01
	700	15.6	23.65	48	0.504	2.04/1.6	1/47	7.00	87750	>1000'	23.35	5.15
			47.3	96	1.008						47.3	22.5
		26.8	35.4	48	0.376	1.356/1.4	1/94.1	7.00	21900	450'	16.51	3.25
			70.8	96	0.752						33.0	12.01
	900	15.6	21.6	48	0.504	2.22/1.6	1/42.9	7.00	105600	>1000'	23.6	5.15
			43.2	96	1.008						47.6	22.5
		26.8	34.6	48	0.376	1.39/1.4	1/92	7.00	22950	550	16.55	3.25
			69.2	96	0.752						33.0	12.01
30	300	15.6	28.6	48	0.542	1.68/1.6	1/52.75	7.15	71250	>1000'	24.45	5.15
			57.2	96	1.084						49.4	22.5
		26.8	36.55	48	0.3975	1.315/1.3	1/92	7.00	22900	540'	17.9	3.25
			73.1	96	0.795						34.7	12.01
	500	15.6	25.65	48	0.542	1.87/1.6	1/47.4	7.02	86800	>1000'	24.7	5.15
			51.3	96	1.084						50.0	22.5
		26.8	35.4	48	0.401	1.356/1.4	1/88.25	7.00	24950	790'	17.59	3.25
			70.8	96	0.802						34.95	12.01
	700	15.6	23.3	48	0.542	2.06/1.6	1/43	7.00	105000	>1000'	24.93	5.15
			46.6	96	1.084						50.4	22.5
		26.8	34.4	48	0.401	1.40/1.4	1/85.75	7.01	26,400	1000'	17.62	3.25
			68.8	96	0.802						35.1	12.01
	900	15.6	21.2	48	0.542	2.26/1.6	1/39.1	7.00	127000	>1000'	25.2	5.15
			42.4	96	1.084						50.95	22.5
		26.8	33.8	48	0.401	1.42/1.4	1/84.3	7.00	27300	>1000'	17.66	3.25
			67.6	96	0.802						35.15	12.01

VALUES OF L' FROM SOLUTION FOR SCANTLINGS

BASED ON $\sigma_1 = 3.0\ L^{0.23}$

H	L	a	b	t	a/b	t/b	k_c	σ_{cr}	L'
10	300	48	34.95	0.234	1.37	1/149.2	7.0	8,710	3.4
	500	"	33.5	0.239	1.43	1/140	7.02	9,925	5.42
	700	"	32.6	0.240	1.47	1/136	7.06	10,600	7.3
	900	"	31.3	0.241	1.53	1/130	7.13	11,700	11.2
15	300	"	34.1	0.284	1.40	1/120	7.0	13,500	20.5
	500	"	32.6	0.285	1.47	1/114.3	7.08	15,000	32.8
	700	"	31.4	0.286	1.53	1/109.9	7.12	16,350	47.6
	900	"	30.4	0.287	1.58	1/106	7.27	17,920	71.5
20	300	"	34.45	0.330	1.39	1/104.2	7.0	17,900	70
	500	"	32.95	0.332	1.455	1/99.25	7.04	19,800	110
	700	"	31.8	0.334	1.51	1/95.2	7.10	21,750	166
	900	"	30.9	0.336	1.55	1/92	7.15	23,400	225
25	300	"	34.85	0.374	1.38	1/93.25	7.0	22,300	185
	500	"	33.55	0.378	1.43	1/88.75	7.03	24,750	290
	700	"	32.35	0.380	1.485	1/85.2	7.08	27,050	425
	900	"	31.4	0.382	1.53	1/82.3	7.12	29,100	580
30	300	"	34.2	0.401	1.4	1/85.2	7.0	26,750	410
	500	"	32.6	0.403	1.47	1/81	7.06	29,800	650
	700	"	31.4	0.4045	1.53	1/77.8	7.12	32,600	960
	900	"	30.5	0.406	1.575	1/75	7.22	35,600	1400

VALUES OF γ FOR $\sigma_1 = 3.0L^{0.23}$

H	L	a	σ_{cr}	t	b_{new}	STIFFENER #/ft.	γ
10	300	48	25,000	0.234	20.6	7.0	13.7
		96		0.468	41.2	14.91	23.6
	500	48	28,150	0.239	19.82	7.0	14.06
		96		0.478	39.64	14.91	24.15
	700	48	30,400	0.240	19.2	7.0	14.24
		96		0.480	38.4	14.91	24.4
	900	48	32,200	0.241	18.7	7.0	14.39
		96		0.482	37.4	14.91	24.6
15	300	48	25,000	0.284	25.0	8.25	15.62
		96		0.568	50.0	20.06	28.2
	500	48	28,150	0.285	23.65	8.25	15.9
		96		0.570	47.3	20.06	28.5
	700	48	30,400	0.286	22.85	8.25	16.09
		96		0.572	45.7	20.06	28.75
	900	48	32,200	0.287	22.25	8.25	16.26
		96		0.574	44.5	20.06	29.0
20	300	48	25,000	0.330	29.05	8.25	16.99
		96		0.660	58.1	20.06	31.2
	500	48	28,150	0.332	27.55	8.25	17.24
		96		0.664	55.1	20.06	31.6
	700	48	30,400	0.334	26.65	8.25	17.45
		96		0.668	53.3	20.06	32.0
	900	48	32,200	0.336	26.05	8.25	17.6
		96		0.672	52.1	20.06	32.25
25	300	48	25,000	0.374	33.0	9.5	18.8
		96		0.748	66.0	34.0	36.95
	500	48	28,150	0.378	31.63	9.5	19.15
		96		0.756	63.26	34.0	37.5
	700	48	30,400	0.380	30.3	9.5	19.35
		96		0.760	60.6	34.0	38.0
	900	48	32,200	0.382	29.65	9.5	19.55
		96		0.764	59.3	34.0	38.3
30	300	48	-	0.401	34.2	3.25	17.64
		96	-	0.802	64.8	12.01	35.2
	500	48	-	0.403	32.6	3.25	17.77
		96	-	0.806	65.2	12.01	35.35
	700	48	-	0.4045	31.4	3.25	17.89
		96	-	0.809	62.8	12.01	35.55
	900	48	-	0.406	30.5	3.25	18.0
		96	-	0.812	61.0	12.01	35.8

VALUES OF L' FROM SOLUTION FOR SCANTLINGS

BASED ON $\sigma_1 = 4.123\ L^{0.23}$ BASIS

H	L	a	b	t	a/b	t/b	k_c	σ_{cr} clamped	L'
10	300	48	30.05	0.2425	1.595	1/124	7.1	12,800	4.13
		96	60.10	0.485	"	"	"	"	
	500	48	27.2	0.2425	1.765	1/112.1	7.08	15,600	9.8
		96	54.4	0.485	"	"	"	"	
	700	48	25.0	0.2425	1.92	1/103	7.0	18,300	15.5
		96	50.0	0.485	"	"	"		
	900	48	22.8	0.2425	2.10	1/94	7.0	21,950	43.5
		96	45.6	0.485	"	"	"		
15	300	48	29.2	0.288	1.643	1/101.4	7.20	19,400	25.4
		96	58.4	0.576	"	"	"	"	
	500	48	26.4	0.288	1.82	1/91.7	7.05	23,250	56
		96	52.8	0.576	"	"	"	"	
	700	48	24.2	0.288	1.98	1/84	7.0	27,500	115
		96	48.4	0.576	"	"	"	"	
	900	48	22.15	0.288	2.165	1/76.9	7.0	32,800	245
		96	44.3	0.576	"	"	"	"	
20	300	48	29.75	0.3385	1.614	1/88	7.3	26,150	92
		96	59.5	0.677	"	"	"	"	
	500	48	26.85	0.3385	1.79	1/79.3	7.06	31,150	197.5
		96	53.7	0.677	"	"	"	"	
	700	48	24.7	0.3385	1.94	1/73	7.0	36,400	390
		96	49.4	0.677					
	900	48	22.6	0.3385	2.12	1/66.9	7.0	43,500	840
		96	45.2	0.677					
25	300	48	30.15	0.384	1.593	1/78.5	7.3	32,850	250
		96	60.3	0.768					
	500	48	27.25	0.384	1.76	1/71	7.1	39,100	530
		96	54.5	0.768					
	700	48	25.0	0.384	1.92	1/65	7.0	46,000	1092
		96	50.0	0.768					
	900	48	22.9	0.384	2.095	1/59.7	7.0	54,500	2250
		96	45.8	0.768					
30	300	48	29.2	0.408	1.645	1/71.5	7.2	39,000	525
		96	58.4	0.816	"	"	"	"	"
	500	48	26.45	0.408	1.813	1/64.9	7.05	46,500	1120
		96	52.9	0.816	"	"	"	"	"
	700	48	24.3	0.408	1.975	1/59.5	7.0	54,800	2180
		96	48.6	0.816	"	"	"	"	"
	900	48	22.2	0.408	2.16	1/54.5	7.0	65,250	4900
		96	44.4	0.816	"	"	"	"	"

VALUES OF γ FOR $\sigma_1 = 4.123\ L^{0.23}$

H	L	σ_{cr}	t	a	b_{orig}	b_{new}	a/b	STIFFENER #/ft.	γ
10	300	34,400	0.2425	48	30.05	18.2	>1.6	7.0	14.6
			0.485	96	60.1	36.4		12.01	23.9
	500	38,700	0.2425	48	27.2	17.18	>1.6	7.0	14.84
			0.485	96	54.4	34.36		12.01	24.10
	700	41,750	0.2425	48	25.0	16.52	>1.6	7.0	15.1
			0.485	96	50.0	33.04		12.01	24.35
	900	46,500	0.2425	48	22.8	15.7	>1.6	7.0	15.3
			0.485	96	45.6	31.4		12.01	24.5
15	300	34,400	0.288	48	29.2	21.65	>1.6	8.25	16.41
			0.576	96	58.4	43.3		20.06	29.35
	500	38,700	0.288	48	26.4	20.4	>1.6	8.25	16.7
			0.576	96	52.8	40.8		20.06	29.6
	700	41,760	0.288	48	24.2	19.62	>1.6	8.25	16.9
			0.576	96	48.4	39.24		20.06	29.8
	900	46,500	0.288	48	22.15	18.6	>1.6	8.25	17.19
			0.576	96	44.3	37.2		20.06	30.2
20	300	34,400	0.3385	48	29.75	25.4	>1.6	8.25	17.8
			0.677	96	59.5	50.8		20.06	32.55
	500	38,700	0.3385	48	26.85	23.95	>1.6	8.25	18.05
			0.677	96	53.7	47.9		20.06	32.8
	700	41,750	0.3385	48	24.7	23.05	>1.6	8.25	18.21
			0.677	96	49.4	46.1		20.06	33.0
	900	46,500	0.3385	48	22.6	21.85	>1.6	8.25	18.42
			0.677	96	45.2	43.7		20.06	33.35
25	300	34,400	0.384	48	30.15	28.8	>1.6	9.5	19.76
			0.768	96	60.3	57.6		34.0	38.6
	500	38,700	0.384	48	27.25	-	>1.6	3.25	17.23
			0.768	96	54.5	-		12.01	34.25
	700	41,750	0.384	48	25.0	-	>1.6	3.25	17.35
			0.768	96	50.0	-		12.01	34.4
	900	46,500	0.384	48	22.9	-	>1.6	3.25	17.5
			0.768	96	45.8	-		12.01	34.8
30	300	34,400	0.408	48	29.2	-	>1.6	3.25	18.1
			0.816	96	58.4	-		12.01	36.05
	500	38,700	0.408	48	26.45	-	>1.6	3.25	18.26
			0.816	96	52.9	-		12.01	36.2
	700	41,750	0.408	48	24.3	-	>1.6	3.25	18.4
			0.816	96	48.6	-		12.01	36.55
	900	46,500	0.408	48	22.2	-	>1.6	3.25	18.5
			0.816	96	44.4	-		12.01	36.8

Differences in Structural Specific Weight for 48" and 96" Web Frame Spacings and σ_y

H	L	$\sigma_y = 15.6$ Khoushy	$\sigma_y = 26.8$ Tobin	$\sigma_y = 26.8$ Khoushy	$\sigma_y = 26.8$ $3.0L^{0.23}$	$\sigma_y = 26.8$ $4.1L^{0.23}$	H	L	$\sigma_y = 15.6$ Khoushy	$\sigma_y = 26.8$ Tobin	$\sigma_y = 26.8$ Khoushy	$\sigma_y = 26.8$ $3.0L^{0.23}$	$\sigma_y = 26.8$ $4.1L^{0.23}$
10	300	13.8	9.81	10.85	9.9	9.3	10	300	↑	↑	↑	↑	↑
	500	13.96	9.90	10.89	10.09	9.26		500	13.96	9.81	10.89	10.29	9.25
	700	14.0	9.93	10.93	10.16	9.25		700	(AVERAGE)	(AVERAGE)	(AVERAGE)	(AVERAGE)	(AVERAGE)
	900	14.1	9.98	10.87	10.21	9.2		900	↓	↓	↓	↓	↓
15	300	16.85	12.18	12.52	12.58	12.94	15	300	↑	↑	↑	↑	↑
	500	17.10	12.28	12.62	12.6	12.9		500	17.12	12.32	12.65	12.65	12.94
	700	17.19	12.34	12.71	12.66	12.9		700	(AVERAGE)	(AVERAGE)	(AVERAGE)	(AVERAGE)	(AVERAGE)
	900	17.35	12.48	12.76	12.74	13.01		900	↓	↓	↓	↓	↓
20	300	19.65	13.82	14.23	14.21	14.75	20	300	↑	↑	↑	↑	↑
	500	19.8	14.01	14.25	14.36	14.75		500	19.90	14.03	14.41	14.44	14.80
	700	200	14.11	14.56	14.55	14.79		700	(AVERAGE)	(AVERAGE)	(AVERAGE)	(AVERAGE)	(AVERAGE)
	900	20.15	14.20	14.60	14.69	14.93		900	↓	↓	↓	↓	↓
25	300	23.25	16.1	17.75	18.15	18.84	25	300	↑	↑	↑	↑	↑
	500	23.48	16.19	17.91	18.35	17.02		500	23.67	16.23	18.01	18.48	17.55
	700	23.95	16.28	18.05	18.65	17.05		700	(AVERAGE)	(AVERAGE)	(AVERAGE)	(AVERAGE)	(AVERAGE)
	900	24.0	16.35	18.35	18.75	17.3		900	↓	↓	↓	↓	↓
30	300	24.95	17.05	17.11	17.56	17.95	30	300	↑	↑	↑	↑	↑
	500	25.3	17.15	17.20	17.58	17.94		500	25.36	17.18	17.26	17.65	18.09
	700	25.47	17.20	17.35	17.66	18.15		700	(AVERAGE)	(AVERAGE)	(AVERAGE)	(AVERAGE)	(AVERAGE)
	900	25.72	17.32	17.40	17.80	18.30		900	↓	↓	↓	↓	↓

Values of Structural Specific Weight from Transition Lines for σ_1 Criteria

L	H	a	t	b	a/b	Stiffener #/FT	γ	a	t	b	a/b	Stiffener #/FT	γ
300	22.4	↑	0.350	39.9	1.2	8.25	16.89	↑	0.700	79.8	1.2	20.06	31.75
	26.2		0.380	37.5	1.28	9.5	18.63		0.760	75.0	1.28	34.0	36.7
	26.0		0.3815	34.85	1.378	9.5	18.92		0.763	69.7	1.378	34.0	37.2
	27.75		0.402	30.0	1.6	9.5	20.3		0.809	60.0	1.6	34.0	39.8
500	24.6	48	0.367	38.3	1.25	9.5	18.19	96	0.734	76.6	1.25	34.0	35.5
	27.0		0.387	36.15	1.33	9.5	19.05		0.774	72.3	1.33	34.0	37.4
	24.6		0.372	33.2	1.445	9.5	18.75		0.744	66.4	1.445	34.0	36.7
	28.2		0.406	27.15	1.77	9.5	20.9		0.812	54.3	1.77	34.0	40.95
700	26.1		0.381	37.55	1.28	9.5	18.7		0.765	65.0	1.28	34.0	37.7
	27.55	48	0.392	35.1	1.37	9.5	19.4	96	0.784	70.2	1.37	34.0	38.1
	22.7		0.361	32.25	1.49	8.25	17.9		0.722	64.5	1.49	20.06	36.1
	27.95		0.405	25.0	1.92	9.5	21.2		0.810	50.0	1.92	34.0	41.1
900	26.8		0.3855	36.6	1.31	9.5	18.92		0.771	73.2	1.31	34.0	37.4
	27.75		0.396	34.65	1.385	9.5	19.6		0.792	69.3	1.385	34.0	38.45
	20.3		0.3455	31.45	1.52	8.25	17.37		0.691	62.9	1.52	20.06	34.9
	27.4	↓	0.400	22.8	2.1	9.5	21.45	↓	0.800	45.6	2.1	34.0	41.9

NOTE: The sequence of values of draft for each design ship length from top to bottom in order are Tobin, Khoushy, $4.123\,L^{0.23}$ and $3.0\,L^{0.23}$

TABLE OF COMPARATIVE VALUES OF STRUCTURAL SPECIFIC WEIGHT
FOR 48" AND 96" WEB FRAME SPACINGS AND VARIOUS σ_1 CRITERIA

H	L	$\sqrt[3]{L}$	$2.4L^{0.23}$	$3.0L^{0.23}$	$4.1L^{0.23}$
10	300	12.74	13.50	13.7	14.6
		22.55	24.35	23.6	23.9
	500	13.02	13.71	14.06	14.84
		22.92	24.6	24.15	24.10
	700	13.3	13.87	14.24	15.10
		23.23	24.8	24.4	24.35
	900	13.42	13.98	14.39	15.3
		23.4	24.85	24.6	24.5
20	300	16.0	16.62	16.99	17.8
		29.82	30.85	31.2	32.55
	500	16.29	16.85	17.29	18.05
		30.3	31.10	31.6	32.8
	700	16.49	17.19	17.45	18.21
		30.6	31.75	32.0	33.0
	900	16.70	17.3	17.6	18.42
		30.9	31.9	32.25	33.35
30	300	17.15	17.19	17.69	18.1
		34.2	34.3	35.2	36.05
	500	17.30	17.35	17.77	18.26
		34.45	34.55	35.35	36.2
	700	17.4	17.5	17.89	18.4
		34.6	34.85	35.55	36.55
	900	17.48	17.6	18.0	18.5
		34.8	35.0	35.8	36.8

H	L	$\sqrt[3]{L}$	$2.4L^{0.23}$	$3.0L^{0.23}$	$4.1L^{0.23}$
15	300	14.62	15.28	15.62	16.41
		26.8	27.8	28.2	29.35
	500	14.92	15.55	15.9	16.7
		27.2	28.15	28.5	29.6
	700	15.16	15.69	16.09	16.9
		27.5	28.4	28.75	29.8
	900	15.32	15.79	16.26	17.19
		27.8	28.55	29.0	30.2
25	300	16.0	18.4	18.8	19.76
		32.1	36.15	36.95	38.6
	500	16.06	18.69	19.15	*17.23
		32.55	36.60	37.5	*34.25
	700	16.12	18.85	19.35	*17.35
		32.4	36.9	38.0	*34.4
	900	16.2	19.00	19.55	*17.5
		32.55	37.35	38.3	*34.8

* THESE VALUES ARE LESS THAN PRECEEDING VALUES DUE TO TRANSITION TO YIELD DESIGN CRITERIA

WEIGHT SAVINGS OF 26.8 T/in^2 OVER 15.6 T/in^2 STEEL FOR σ_1 CRITERIA

t	L	KHOUSHY 15.6	TOBIN 26.8	δW	%	KHOUSHY 26.8	δW	%	$3.0L^{0.23}$ 26.8	δW	%	$4.123L^{0.23}$ 26.8	δW	%
10	300	13.95	12.74	1.21	8.79	13.5	0.45	3.22	13.7	0.25	1.79	14.6	-0.65	-4.65
		27.75	22.55	5.20	18.75	24.35	3.4	12.25	23.6	4.15	14.9	23.9	3.85	13.89
	500	14.04	13.02	1.02	7.27	13.71	0.33	2.35	14.06	-0.02	-1.425	14.84	-0.80	-5.70
		28.0	22.92	5.08	18.12	24.6	3.4	12.12	24.15	3.85	13.75	24.10	3.90	13.91
	700	14.15	13.3	0.85	6.0	13.87	0.28	1.98	14.24	-0.09	-6.35	15.1	-0.95	-6.71
		28.15	23.23	4.92	17.5	24.8	3.35	11.9	24.4	3.75	13.31	24.35	3.80	13.50
	900	14.3	13.42	0.88	6.15	13.98	0.32	2.24	14.39	-0.09	-6.30	15.3	-1.0	-7.0
		28.4	23.4	5.0	17.6	24.85	3.55	12.5	24.6	3.8	13.39	24.5	3.90	13.71
15	300	17.15	14.62	2.53	14.75	15.28	1.87	10.9	15.62	1.53	8.93	16.41	0.74	4.31
		34.0	26.8	7.2	21.2	27.8	6.2	18.25	28.2	5.8	17.05	29.35	4.65	13.70
	500	17.35	14.92	2.43	14.0	15.55	1.8	10.39	15.9	1.45	8.35	16.7	0.65	3.75
		34.45	27.2	7.25	21.0	28.15	6.3	18.3	28.5	5.95	17.28	29.6	4.85	14.09
	700	17.51	15.16	2.35	13.4	15.69	1.82	10.39	16.09	1.42	8.10	16.9	0.61	3.48
		34.7	27.5	7.2	20.75	28.4	6.3	18.15	28.75	5.95	17.15	29.8	4.9	14.11
	900	17.6	15.32	2.28	12.95	15.79	1.81	10.29	16.26	1.34	7.52	17.19	0.41	2.33
		34.95	27.8	7.15	20.45	28.55	6.4	18.3	29.0	5.95	17.01	30.2	4.75	13.6
20	300	20.55	16.0	4.55	22.15	16.62	3.93	19.1	16.99	3.56	17.3	17.8	2.75	13.39
		40.2	29.82	10.38	25.8	30.85	9.35	23.25	31.2	9.0	22.4	32.55	7.65	19.0
	500	20.8	16.29	4.51	21.7	16.85	3.95	19.0	17.24	3.56	17.1	18.05	2.75	13.2
		40.6	30.3	10.3	25.35	31.10	9.5	23.35	31.6	9.0	22.2	32.8	7.8	19.2
	700	21.0	16.49	4.51	21.45	17.19	3.81	18.15	17.45	3.55	16.9	18.21	2.79	13.29
		41.0	30.6	10.4	25.4	31.75	9.25	22.55	32.0	9.0	21.95	33.0	8.0	19.5
	900	21.25	16.70	4.55	21.4	17.3	3.95	18.6	17.6	3.65	17.15	18.42	2.83	13.30
		41.4	30.9	10.5	25.4	31.90	9.5	23.0	32.25	9.15	22.15	33.35	8.05	19.48
25	300	22.75	16.0	6.75	29.65	18.4	4.35	19.15	18.8	3.95	17.35	19.76	2.99	13.13
		46.0	32.1	13.9	30.2	36.15	9.85	21.4	36.95	9.05	19.7	38.6	7.4	16.1
	500	23.07	16.06	7.01	30.4	18.69	4.38	19.0	19.15	3.92	17.0	17.23	5.84	25.25
		46.55	32.25	14.3	30.7	36.60	9.95	21.35	37.5	9.05	19.4	34.25	12.30	26.4
	700	23.35	16.12	7.23	31.0	18.85	4.50	19.26	19.35	4.0	17.12	17.35	6.0	25.7
		47.3	32.4	14.9	31.55	36.9	10.4	22.0	38.0	9.3	19.7	34.4	12.9	27.3
	900	23.6	16.20	7.4	31.3	19.00	4.6	19.47	19.55	4.05	17.15	17.5	6.1	25.8
		47.6	32.55	15.05	31.6	37.35	10.25	21.5	38.3	9.3	19.55	34.8	12.8	26.85
30	300	24.45	17.15	7.3	29.85	17.19	7.26	29.7	17.64	6.81	27.85	18.1	6.35	26.0
		49.4	34.2	15.2	30.8	34.3	15.1	30.6	35.2	14.2	28.8	36.05	13.35	27.05
	500	24.7	17.30	7.4	30.0	17.35	7.35	29.75	17.77	6.93	28.05	18.26	6.44	26.0
		50.0	34.45	15.55	31.15	34.55	15.45	30.9	35.35	14.65	29.3	36.2	13.8	27.6
	700	24.93	17.40	7.53	30.2	17.5	7.43	29.75	17.89	7.04	28.2	18.4	6.53	26.2
		50.4	34.6	15.8	31.4	34.85	15.55	30.9	35.55	14.85	29.5	36.55	13.85	27.5
	900	25.2	17.48	7.72	30.6	17.6	7.6	30.15	18.0	7.2	28.55	18.5	6.7	26.8
		50.92	34.8	16.12	31.7	35.0	15.92	31.35	35.8	15.12	29.75	36.8	14.12	27.8

DIFFERENCES CITED ARE FOR THE GIVEN Υ VALUE FOR THE APPROPRIATE σ_1 CRITERION MINUS THE Υ VALUE FOR 15.6 T/in^2 STEEL AS DETERMINED USING THE KHOUSHY CRITERION FOR σ_1.

STRUCTURAL SPECIFIC WEIGHT COMPARISON FOR DIFFERENT STIFFENER MATERIALS FOR VALUES ON TRANSITION LINE

H	L	a	b	t	Steel (instab.)	τ	Steel (yield)	τ	Al stiffener	τ	Be stiffener	τ	%δτ Steel	%δτ Al	%δτ Be	% stiffener
22.4	300	48	39.9	0.350	9.5	17.26	2.75	15.2	3.25	15.38	1.908	14.91	11.96	10.9	13.61	16.51
		96	79.8	0.700	34.0	33.9	11.0	30.4	11.62	30.5	4.62	29.4	10.3	10.0	13.29	15.09
24.6	500	48	38.3	0.367	9.5	18.19	2.75	15.95	3.25	16.10	2.195	15.62	12.31	11.5	14.15	16.35
		96	76.6	0.734	34.0	35.5	11.0	31.9	11.62	32.0	7.85	31.4	10.13	9.87	11.55	14.98
26.1	700	48	37.55	0.381	9.5	18.7	3.25	17.13	3.25	16.68	2.195	16.40	8.4	10.8	12.3	16.25
		96	75.1	0.762	34.0	36.8	12.01	34.1	11.62	33.2	7.85	33.15	9.55	9.79	12.1	14.72
26.8	900	48	36.6	0.3855	9.5	18.92	3.25	16.92	3.25	16.92	2.195	16.59	10.6	10.55	12.3	16.45
		96	73.2	0.771	34.0	37.4	12.01	33.75	11.62	33.7	7.85	33.0	9.76	9.9	11.76	14.9
26.2	300	48	37.5	0.380	9.5	18.63	3.25	16.65	3.25	16.65	2.195	16.28	10.6	10.73	12.6	16.31
		96	75.0	0.760	34.0	36.7	12.01	33.1	11.62	33.0	7.85	32.45	9.81	10.1	11.6	14.8
27.0	500	48	36.15	0.387	9.5	19.05	3.25	16.99	3.25	16.99	2.195	16.64	10.8	10.8	12.65	16.55
		96	72.3	0.774	34.0	37.4	12.01	33.8	11.62	33.7	7.85	33.05	9.625	9.9	11.61	15.09
27.55	700	48	35.1	0.392	9.5	19.4	3.25	17.21	3.25	17.21	2.195	16.87	11.3	11.28	13.02	16.75
		96	70.2	0.784	34	38.1	12.01	34.3	11.62	34.3	7.85	33.6	9.97	10.0	11.8	15.22
27.75	900	48	34.65	0.396	9.5	19.6	3.25	17.40	3.25	17.4	2.195	17.03	11.23	11.21	13.1	16.8
		96	69.3	0.792	34.0	38.45	12.01	34.65	11.62	34.5	7.85	33.85	9.88	10.27	11.96	15.3
26.0	300	48	34.85	0.3815	9.5	18.92	3.25	16.79	3.25	16.79	2.195	16.41	11.25	11.26	13.3	17.29
		96	69.7	0.763	34.0	37.2	12.01	33.4	11.62	33.4	7.85	32.75	10.2	10.2	14.66	15.71
24.6	500	48	33.2	0.372	9.5	18.75	2.75	16.29	3.25	16.45	2.195	16.08	13.67	12.27	14.25	18.31
		96	66.4	0.744	34.0	36.7	11.0	32.58	11.62	32.6	7.85	31.95	11.23	11.19	12.95	16.71
22.7	700	48	32.25	0.361	9.5	18.35	2.75	15.86	3.25	16.03	1.908	15.53	13.69	12.63	15.38	19.28
		96	64.5	0.722	34.0	36.0	11.0	31.72	11.62	31.9	4.62	30.55	13.55	11.4	15.13	17.52
20.3	900	48	31.45	0.3455	9.5	17.75	2.75	15.23	3.25	15.45	1.908	14.92	14.2	12.97	15.95	20.4
		96	62.9	0.691	34.0	34.95	11.0	30.46	11.62	30.65	4.62	29.25	12.84	12.3	16.3	18.55
27.7	300	48	30.0	0.402	9.5	20.3	3.25	17.81	3.25	17.81	2.195	17.39	12.28	12.27	14.33	18.71
		96	60.0	0.804	34.0	39.8	12.01	35.4	11.62	35.35	7.85	34.6	11.05	11.19	13.06	17.09
28.2	500	48	27.15	0.406	9.5	20.9	3.25	18.10	3.25	18.10	2.195	17.64	13.4	13.4	15.6	20.1
		96	54.3	0.812	34.0	40.95	12.01	36.0	11.62	36.05	7.85	35.2	12.1	11.96	11.6	18.35
27.95	700	48	25.0	0.405	9.5	21.2	3.25	18.2	3.25	18.20	2.195	17.72	14.15	14.15	16.4	21.5
		96	50.0	0.810	34.0	41.1	12.01	36.2	11.62	36.1	7.85	35.2	11.9	12.15	14.35	19.81
27.4	900	48	22.8	0.400	9.5	21.95	3.25	18.16	3.25	18.16	2.195	17.87	15.33	15.32	18.1	23.3
		96	45.6	0.800	34.0	41.9	12.01	36.0	11.62	35.9	7.85	34.9	14.1	14.35	16.72	21.3

NOTE: VALUES ARE FOR TOBIN, KHOUSHY, $3.0L^{0.23}$ AND $4.123L^{0.23}$ CRITERIA FOR σ, PROCEEDING FROM TOP TO BOTTOM FOR EACH SET OF LENGTHS

Values of structural loading index $(H/(D/L)^2)$ and Structural Specific Weight for combinations of σ_1 criterion, web frame spacing and σ_y.

H	L	$H/(D/L)^2$	1	2	3	4	5	6	7	8
10	300	4.85×10^3	13.95	27.75	12.74	22.55	13.50	24.35	13.70	23.6
	500	7.3×10^3	14.04	28.0	13.02	22.92	13.71	24.6	14.06	24.15
	700	9.51×10^3	14.15	28.15	13.3	23.23	13.87	24.8	14.24	24.4
	900	11.74×10^3	14.3	28.4	13.42	23.4	13.98	24.85	14.39	246
15	300	3.9×10^3	17.15	34.0	14.62	26.8	15.28	27.8	15.62	28.2
	500	6.8×10^3	17.35	34.45	14.92	27.2	15.55	28.15	15.9	28.5
	700	9.6×10^3	17.51	34.7	15.16	27.5	15.69	28.4	16.09	28.75
	900	12.8×10^3	17.6	34.95	15.32	27.8	15.79	28.55	16.26	29.0
20	300	3.23×10^3	20.55	40.2	16.0	29.82	16.62	30.85	16.99	31.2
	500	6.15×10^3	20.8	40.6	16.29	30.3	16.85	31.10	17.24	31.6
	700	8.78×10^3	21.0	41.0	16.49	30.6	17.19	31.75	17.45	32.0
	900	12.65×10^3	21.25	41.4	16.70	30.9	17.30	31.90	17.6	32.25
25	300	2.75×10^3	22.75	46.0	16.0	32.1	18.40	36.15	18.8	36.95
	500	5.57×10^3	23.07	46.55	16.06	32.25	18.69	36.60	19.15	37.5
	700	8.625×10^3	23.35	47.30	16.12	32.4	18.85	36.90	19.35	38.0
	900	12.2×10^3	23.6	47.6	16.20	32.55	19.00	37.35	19.55	38.3
30	300	2.39×10^3	24.45	49.4	17.15	34.2	19.10	37.70	17.64	35.2
	500	5.06×10^3	24.7	50.0	17.3	34.45	19.44	38.20	17.77	35.35
	700	8.07×10^3	24.93	50.4	17.4	34.6	19.60	38.60	17.89	35.55
	900	11.57×10^3	25.2	50.95	17.48	34.8	19.75	38.90	18.0	35.8

LEGEND FOR COLUMNS ABOVE:

1. Khoushy criterion for σ_1, 48" web frame spacing, 26.8 T/in^2 steel
2. Khoushy criterion for σ_1, 96" web frame spacing, 15.6 T/in^2 steel
3. Tobin criterion for σ_1, 48" web frame spacing, 26.8 T/in^2 steel
4. Tobin criterion for σ_1, 96" web frame spacing, 26.8 T/in^2 steel
5. Khoushy criterion for σ_1, 48" web frame spacing, 26.8 T/in^2 steel
6. Khoushy criterion for σ_1, 96" web frame spacing, 26.8 T/in^2 steel
7. $\sigma_1 = 3.0\, L^{0.23}$, 48" web frame spacing, 26.8 T/in^2 steel
8. $\sigma_1 = 3.0\, L^{0.23}$, 96" web frame spacing, 26.8 T/in^2 steel

APPENDIX B

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